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LASERS, THE PRICE OF ADMISSION IN 2045

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John G. Dayton, Maj, USAF
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Advisors: Lt Col Paul P. Clemans, Maj Thomas E. Kiesling

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PREFACE

The future for the United States Air Force is exciting. Our future will be filled with new technologies and new capabilities beyond our wildest dreams. My research was fueled by this wonder about the possibilities of future airpower. The Air Force Chief of Staff posed the question, "How should the Air Force project power in highly contested environments by 2045?" Although I did not begin this project with any experience in laser weapons, the research built my appreciation for them and their role in future combat. For those readers just awakening to laser weapons, this report should provide evidence to convince you about their role in future warfare. And for laser advocates, I have joined your ranks. I hope this paper gives the technology, and its potential, a fair evaluation.

I also must give special thanks to my research advisors and all others who supported my research. This paper would not have been possible without their enormous support and valuable insights. Thank you!

ABSTRACT

High power laser weapons exist today and will become the "price of admission" for future combat—and it is time to get informed! This study uses open source material to investigate how laser weapons will influence the United States' power projection capabilities in highly contested environments in 2045. Now and in the future, the United States will require air superiority and airpower effects. Laser weapons may be "game-changers" for power projection in the short term; however, the United States can maximize their effectiveness by looking beyond their initial introduction and into the innovation and counter-innovation cycle of future warfare. In a world of increased proliferation, the competition between concepts of operation for laser weapons and the interaction of these new technologies will steer development for both the United States and potential adversaries. Within this framework, this research considers recent developments in laser weapons, re-evaluates the future impact of laser weapons on air superiority and airpower projection, explores the strategic implications of laser weapons, and identifies obstacles to their implementation. Ultimately, this research contends that while laser weapons might be revolutionary in 2030, laser weapons will be the "price of admission" for high-end conventional combat in 2045.

LASERS, THE PRICE OF ADMISSION

Introduction

High power laser weapons exist today and will simply become the "price of admission" for future combat—and it is time to get informed! The most fundamental prerequisite for decisive airpower is command of the air…or air superiority. In order to maintain freedom of action on the land, in the sea, and through the air, the United States needs air superiority, now and in the future. However, air superiority is not an end by itself—airpower must also create strategic effects against the adversary. Directed Energy, and specifically the laser, has long been heralded as a "game-changing" technology that promises to revolutionize both air superiority and airpower projection. This research considers the recent developments in laser weapon technology and re-evaluates the future impact of laser weapons on air superiority and airpower projection in highly contested environments. Ultimately, while laser weapons might be revolutionary in 2030, this research contends that by 2045 laser weapons will be the "price of admission" for high-end conventional combat.

The United States faces significant challenges operating in highly contested environments (anti-access and area denial, or A2/AD). The advancement and proliferation of modern surface-to-air missiles (SAMs), advanced fighter aircraft, electronic attack, and long range standoff weapons combine to degrade the United States' ability to project power. These technologies leave the United States at an operational disadvantage due to its heavy reliance on long-range power projection. Further, the globalized commercial nature of the modern world makes it likely that technology will continue to proliferate, and the United States' asymmetrical advantage in

technology will be more difficult to maintain. As a result, the United States will continue to face challenges in highly contested environments in the future.

If the United States wants to continue to successfully project power, it must attain and maintain the capability to act in these contested environments. One option is to incrementally advance the current technology—to develop "better" aircraft and weapons in larger quantities with more range, speed, capability, and stealth. But technology is advancing and proliferating around the world. In fact in this globalized environment, pursuing only incremental advancement might cede the technological advantage to potential adversaries that explore new fronts in technology.

An alternative option is to introduce revolutionary, or "game-changing," technology to address the strategic and tactical challenges of contested environments. Leveraging the United States' strengths and introducing "off-set" capabilities offer tremendous opportunities for future contested environments.[1] From this standpoint, the following research questions are posed: Would laser weapons offer the United States an alternative option and a "game-changing" advantage? How will laser weapons respond to the cycle of innovation and counter-innovation in warfare? What are the operational and strategic implications of laser weapons? And, if warranted, what are the obstacles to implementing laser weapons?

Advocates for directed energy weapons (DEW) have long proclaimed the "game-changing" potential for laser weapons in future warfare, and answering these research questions will help validate those assertions within the constraints of this analysis. This paper only investigates a subset of directed energy—laser weapons. An essential assumption throughout the analysis is that government priority and resources continue or increase for laser weapon development. While this analysis attempts to consider the entirety of a laser weapon system, additional

assumptions were made for convenience about supporting technologies and are noted throughout the analysis. Although laser weapons also provide excellent sensing and combat identification capability,[2] these applications are not considered. In addition, laser weapon applications from space or relayed through space are beyond the scope of this analysis. This research was conducted using open source and unclassified materials to ensure the broadest audience and to encourage open discussion on the future implications of laser weapons. Specifically, details on laser lethality, countermeasures, laser war-gaming, and state-of-the-art technology may not be available. As a result, this paper uses mostly secondary sources and material. This limits some precision available to the argument, but should not detract from the study's value or overall conclusions.

As the era of laser weapons rushes toward reality, airpower's leaders, strategists, and tacticians must recognize the potential of this new technology and prepare for change. Laser weapons are receiving significant attention from scientists and some senior leaders, but broad acceptance, critical thinking, and planning are lacking throughout the force. This paper will consider recent developments in laser weapons, re-evaluate the impact of laser weapons on air superiority and airpower projection, explore the operational and strategic implications of laser weapons in 2045, and identify obstacles to their implementation. Ultimately, this paper should motivate continued research and more widespread critical thought on the future role of laser weapons.

This paper argues that laser weapons will significantly change the tactics and strategy of air superiority and airpower projection in the future. By 2045, lasers will be the "price of admission" in highly contested environments, for both defensive and offensive actions. The following main points are demonstrated through the analysis:

- Laser weapons offer solutions for current and future challenges—both strategic and operational
- Laser weapons will revolutionize airpower projection but will quickly become the "price of admission" for future combat
- The side with the most advanced laser weapons and the best tactics will have a distinct advantage in future combat
- Future mission priority for laser weapons will be: Counter-Directed Energy, Counter-Sensor, Area/Self-Defense, Offensive Fires
- Failure to incorporate defensive laser weapons or failure to defend against laser weapons will increase vulnerability to attack
- Failure to incorporate laser weapons into offensive operations will limit combat effectiveness
- Despite the progress in laser weapon research, there are still significant obstacles to implementation

It is true that laser weapons have suffered from past setbacks, overly optimistic predictions, and slow progress in research. However, recent developments suggest that the era of laser weapons is dawning both in the United States and around the world. Decisions are being made today that steer the future of laser warfare. Laser weapons promise to address many challenges and build synergy with traditional capabilities in future combat, but the warfighter must be prepared to integrate laser weapons across the joint team.

Evolution of Airpower Strategy and Technology

The strategy and technology of airpower are closely linked. New technology has been promised in the past as a panacea that encouraged speculation on new war-winning strategies that never materialized. However, lofty strategic goals have also been the catalyst for significant research and technological advancement. Since the beginning of warfare, the continuous struggle for military advantage has driven the cycle of innovation and counter-innovation—in

strategy and technology. The aircraft and airpower strategy provide only one example. Since the first "game-changing" introduction of aircraft onto the battlefield, airpower strategy has evolved, and airpower is now ubiquitous in combat. Countries will continue to seek advantages in strategy and technology. As new technologies advance and proliferate around the world, the United States must continuously strive to maintain its advantage.

A nation's economic power also gives context to the development of both strategy and technology. The innovation, counter-innovation cycle in military power can be expensive to develop and maintain. The race to gain advantage may even provide significant strategic effect on its own. Over the past half-century, this innovation cycle has led the United States to its current position where high-tech platforms and expendable "bullets" are costly (and maybe unaffordable). The United States' power projection strategy with current advanced technology is losing the cost exchange with the adversary. Unchecked, this adverse cost exchange could eventually translate to reduced power projection capability and strategic defeat for the United States.

New strategies and technologies that offer an operational advantage and reverse the cost exchange are required if the United States wants to maintain the strategic benefits of a power projection strategy. Laser weapons may offer that potential.

Evolution of Air Theory and Doctrine

Airpower has proven an essential element of combat success. The strategy and technology of airpower have evolved over the past century of air combat, but two overarching factors have remained constant. First, air superiority is essential for airpower employment. Air superiority provides force preservation and an essential force multiplier for land and sea power —both offensively and defensively. Second, airpower provides an offensive capability to create military

or strategic effects through the air. Increased investments and cycles of innovation and counter-innovation for airpower all seek advantage within these two lines of effort.

Early air theorists, such as Giulio Douhet and Billy Mitchell, viewed the introduction of the aircraft as "game-changing." After witnessing the aircraft's tepid introduction during World War I (WWI), these theorists sought to revolutionize the face of warfare. However, while it is certainly true that the airplane revolutionized combat, these theorists failed to anticipate the long-term innovation, counter-innovation cycle in the air. If strategy and technology were stagnant—frozen in 1919—perhaps more of their conclusions would hold true. But radar was developed. Proximity fusing for flak improved air defenses. Advances in aerodynamics and aircraft construction improved fighter aircraft for defensive counter-air. And the cycle continues. History shows that the tools of war are continuously altered by new technology, but strategic competition continues.

Modern air theory has converged. The most fundamental prerequisite for decisive airpower is command of the air…or air superiority. This airpower tenet was first recognized by Douhet, remains true today, and will still be binding in the future. Offensively, freedom of action on the land, in the sea, and through the air depends on air superiority. Defensively, air superiority denies the enemy the ability to attack through the air and protects friendly forces. Distinction between superiority and supremacy is important; while geographically and temporally localized air superiority is required, full time air supremacy may be unnecessary or unachievable in future conflict. Ultimately, as new technology is developed, the United States must aggressively pursue the ability to operate in and/or through the air and, when necessary, to prevent the adversary from doing the same.

Once air superiority is attained, then airpower can accomplish "something strategically useful in the air."[3] But even if no other action is taken by airpower, air superiority itself provides strategic effect by enabling other forces or other instruments of power. At the other end of the airpower spectrum, an almost entirely air-centric campaign might provide decisive strategic effects in certain conflicts. Airpower will always seek out new technology and new tactics to achieve even greater strategic value and precision of effect.

Technology, Innovation, and Counter-Innovation

Warfare has undergone continuous cycles of innovation and counter-innovation in tactics and technology in an effort to gain military advantage and ultimately create strategic effects. Airpower innovation spawns new tactics and counter-tactics, new weapons, countermeasures, and counter-countermeasures. History provides a well-established pattern in air-to-air combat, surface-to-air defenses, and air-to-ground munitions. New "game-changing" technology revolutionizes the tools and tactics of combat, but the cycle of innovation quickly provides a counter. Even when these "game-changing" breakthroughs render older technologies obsolete or less effective, counter-innovations follow. The aircraft, radar, infrared sensors, and precision weapons demonstrate this innovation cycle and provide an understanding that is paramount for predicting the role of future technology in conflict.

Aircraft technology itself was introduced to seek advantage for surveillance and artillery spotting to gain advantage in ground conflict. Once the new technology was available, new applications were developed to exploit and to counter the aircraft. The aircraft revolutionized warfare, but the aircraft and airpower became the "price of admission" for future conflicts. The cycle of technology competition moved to the air. One of the earliest significant counter-innovations to aircraft was radar.

Radar provides a useful example of the innovation cycle. Radar identified an adversary's position in the air, and this knowledge provided the ability for early warning and tracking of aircraft during World War II. Radar joined the innovation cycle and soon offered the potential to guide air-to-air and surface-to-air missiles. Soon after WWII, the first radar-guided surface-to-air missile, the Nike Ajax, became operational in 1954.[4] Radar technology quickly decreased in size and weight for airborne applications, and both tactics and technology responded. Aircraft exploited the early radar's filtering, resolution, and beam limitations with tactics such as low-altitude flight, maneuver, and notching. Technology that added jamming and chaff were met with counter-innovations to improve radar filtering, signal processing, and radar performance. As the cycle continued, advanced jamming and stealth technologies further degraded radar's effectiveness. Recently, much concern has been raised about the capability of bistatic radar technology against stealth aircraft. Even today, technology and tactics are being modified to increase radar range, improve performance, and counter the most advanced radar and counter-radar technologies. No doubt this cycle will continue. Technology advances are not static—they quickly become an element of competition for high-end combat.

Infrared systems followed a similar innovation, counter-innovation cycle. Early infrared air-to-air and surface-to-air systems were limited. But once introduced, exploiting or defeating these infrared systems became an essential element of combat. Flares added a countermeasure to defeat early seekers. Flare rejection logic defeated flares as infrared counter-countermeasure (IRCCM) technology improved. More advanced missiles, flares, and IRCCM followed. More recent innovations provide missile warning systems and infrared "jamming" techniques using a laser infrared countermeasure. Large Aircraft Infrared Countermeasure (LAIRCM) is a laser-jamming device used against infrared missiles by the United States today on heavy aircraft.

Again, there is no sign that the cycle of technological revolution, innovation, and counter innovation has run its course; new technologies and tactics are certain.

Innovations in air-to-ground precision show similar trends. Air forces have long sought increasing precision in an effort to achieve even more precise effects, reduce collateral damage, and improve efficiency. The Norden bombsight, computer aided delivery points, laser guided munitions, and Global Positioning System (GPS) guided weapons have dramatically decreased the number of weapons required per target. Today, one single precision-guided bomb can achieve the same effects that required large formations of bombers and thousands of bombs during World War II. Counter-innovations in Integrated Air Defense Systems (IADS), hardened targets, laser jammers, and GPS jamming all aim to deny precision weapon effects. The trend remains clear; the competition between innovation and counter-innovation continues.

With each round of innovation and counter-innovation, the power of technology was re-emphasized. Tactics, technology, or strategy must adapt to remain competitive. Most importantly, when revolutionary "game-changing" technologies—such as aircraft, radar, and precision—entered combat, they quickly became common and the "price of admission" for future combat.

Rising Costs of Combat

The United States enjoyed a significant strategic and technological advantage at the end of the Cold War, but this dynamic is changing. The operational and fiscal costs of combat are rising for the United States, in part, due to the advancement of anti-access and area denial (A2/AD) technologies. The AirSea Battle office is tasked to develop innovative concepts to address A2/AD challenges and describes the problem as follows:

> A2/AD capabilities are those, which challenge and threaten the ability of U.S. and allied forces to both get to the fight and to fight effectively once there. … By

> acquiring these advanced A2/AD technologies, potential adversaries are changing the conditions of warfare that the U.S. has become accustomed to in the past half century. … A new generation of cruise, ballistic, air-to-air, and surface-to-air missiles with improved range, accuracy, and lethality is being produced and proliferated. … The range and scale of possible effects from these capabilities presents a military problem that threatens the U.S. and allied expeditionary warfare model of power projection and maneuver. … Such an environment induces instability, erodes the credibility of U.S. deterrence, can necessitate escalation in U.S. and allied responses, and weakens U.S. international alliances.[5]

Since the Cold War, the United States has followed an investment strategy that prioritizes quality over quantity and seeks to maintain an asymmetric technological advantage over potential adversaries. But airpower's cycle of innovation has driven significant increases in the cost of combat. This investment strategy has served the United States well in the past; however, it is prohibitively expensive to maintain this qualitative force advantage against A2/AD strategies with only incremental advancements in technology. The renewed focus on fiscal constraint exacerbates the challenge. Exploring the argument for a new offset strategy, Robert Martinage argues that, "The United States…cannot afford to simply scale up the current mix of joint power projection capabilities."[6] As the United States seeks a new advantage, the operational and fiscal cost implications must be understood for the new technology and any potential new strategy.

The United States' historical advantage in technology is recognized by potential adversaries and has given rise to A2/AD strategies. The A2/AD strategy seeks to exploit weaknesses in the United States' power projection posture and leverage larger quantities of adversary forces to overwhelm American high-quality (but low density) assets. The strategic costs may be the most significant; these A2/AD strategies impose strategic costs on the United States by creating instability (e.g. encourage first-strike anti-access offensive), increasing strategic vulnerability, and reducing regional deterrence credibility.

At the same time, the financial costs of weapon systems and projected engagements have increased significantly. A decisive technological advantage is even more costly and difficult for the United States to maintain due to rapid widespread proliferation. The anti-access strategy and the proliferation of precision allow relatively low cost weapons to target American bases. The area denial strategy has increased the complexity of air defense systems. The complexity and cost of offensive aircraft to penetrate these defensive systems has soared while the number of available platforms has decreased. The increasing costs of the expendable weapons or "bullets" that these systems employ are also significant. Ultimately, these trends in cost are on a trajectory to make the American style of power projection unaffordable. Increased range, stealth, and improved sensor and sensor logic are not likely to provide the most cost-effective solution. Continued investment in this innovation cycle with the current technologies promises to get more and more expensive.

The rising cost and complexity of military aircraft and air superiority is obvious. The United States may be facing a limit on the value of quality over quantity. Augustine's Law accurately jokes that "in the year 2054, the entire defense budget will purchase just one aircraft."[7] Beyond Augustine's humor, RAND has conducted multiple studies on the rising costs of military aircraft and finds:

> …military aircraft have experienced long-term, unit cost increases that are greater than the rate of inflation. These increases, largely driven by the desire for greater capabilities, appear likely to persist and could have dire implications for aircraft inventories, particularly given relatively fixed defense investment budgets.[8]

For modern and future conflict, this creates a potential face-off between cost and quality. In a modern contested environment, the "price of admission" is a fleet of expensive, advanced, 5+ generation fighter aircraft with stealth, supercruise, maneuverability, long-range munitions, and highly networked sensors. For an adversary unable to match the "price of admission," an

attractive alternative is to employ lower cost aircraft and air defense systems to overwhelm the United States' aircraft in an area denial strategy. The United States needs a larger quantity of aircraft and missiles (and even tanker aircraft) to respond to this denied environment. The reliance on high-end technology and power projection creates unaffordable combat costs for the United States. Ultimately, these costs suggest that the current trend is not tenable.

The United States' power projection strategy shows similar rising costs for air defense at expeditionary locations. Modern air defense systems are no longer limited to striking only the attacking aircraft but can also target incoming munitions. If the United States' air defenses destroy an adversary's aircraft, the cost exchange works; the cost of an aircraft is generally much greater compared to current defensive SAMs. In contrast, the cost of defensive SAMs is much higher than the cost of air-delivered weapons and often more than guided cruise missiles. The concept of overwhelming defenses with higher quantities of low-cost munitions becomes attractive and imposes costs on the defender. Air defense against lower cost munitions becomes unaffordable. This becomes one of the key concerns for the United States when facing anti-access strategies from a more vulnerable power projection posture.

Ongoing analysis of combat in contested environments illustrates this dilemma well. The Center for Strategic and Budgetary Analysis (CSBA) estimated the cost of a hypothetical defensive engagement to counter "anti-access" cruise missile attacks against a forward operating base. The defensive systems included the PATRIOT missile, THAAD missile, and the Standard Missile 3. The report estimates defensive missile costs of $700 million to counter a salvo attack of 30 missiles with a value roughly $105 million (15 percent of the defensive costs).[9] Under a separate Brookings Institute analysis on *Winning the Peace Through Cost Imposition,* Ekman identifies this cost competition between Chinese ballistic missiles and cruise missiles and the

United States' air defenses. Ekman argues that current capabilities force the United States to compete from a position of disadvantage or develop new programs, postures, or operating concepts.[10]

Despite the growing costs of high-end aircraft, air-to-air missiles, and air defense systems, low end precision is now relatively cheap and becoming ubiquitous on the battlefield. Swarm, or saturation attacks, with precision are now possible and affordable. The CSBA is poignant with their conclusion, "the proliferation of precision-guided weapons and other advanced military technologies has *already* changed the game for future U.S. operations."[11] Whether it is air base defense or soldiers in the field, the United States must identify an affordable and effective method to defend against this increased precision.

The interplay of quality and quantity are constantly present in technology and strategy. The rising cost of high-end offensive and defensive systems and reduced cost of low-tech precision are creating new considerations for future investments. Any future technology must consider affordability and effectiveness in an environment with increasing competition between quality and quantity.

Disrupting the Cycle with Laser Weapons

Laser weapons promise to create a major disruption in the current cycle of innovation. In response to A2/AD strategies, cost constraints, and other strategic challenges, laser weapons offer tactical utility, strategic value, and a favorable cost exchange ratio. But, the laser will supplement and complement existing technology just as previous weapon advances have not fully eclipsed earlier technology. Still, laser weapons are a natural step in the cycle of innovation because they reset the cost-exchange equation and solve many technical, tactical, and strategic challenges of operating in a highly contested environment.

Martinage argues for a "third offset" strategy in the United States to leverage areas where the United States holds an advantage in order to maintain deterrence and to counter A2/AD strategies.[12] For example, many cite investments in submarines and stealth bombers as a strategic victory for the United States as part of its competitive strategy against the Soviet Union.[13] Laser weapons fit perfectly into this "offset" strategy. In line with Martinage's argument, the United States is well positioned to lead the "game-changing" introduction of laser weapons due to its technological advantage. The introduction of laser weapons will drive potential adversaries to follow suit and to pay the new "price of admission."

Laser weapons promise many advantages. The deep magazines, low cost per shot, and almost instantaneous weapon flight time (at the speed of light) provide a tactical advantage to any nation that operationalizes this concept. If reliable ground-based defensive laser weapons can be developed, the air defense system performance will increase, and modern munitions may even be unable to reach their targets before being destroyed. Further, the lasers may provide a defensive advantage by imposing significant costs on the attacking force in order to penetrate the defenses. If a reliable airborne self-defense laser can be developed, the traditional priorities for air superiority platforms may be rewritten. Laser power and dwell time on target may replace stealth and maneuverability as development priorities. Will Douhet's concept of a "battleplane" equipped with self-defending laser turrets (rather than the machine gun turrets proposed after WWI) deserve renewed merit? Either way, robust conclusions will require experience and a more detailed understanding of laser weapon technology, limitations, and employment strategy.

Advocates claim that directed energy weapons, including lasers, will "be more revolutionary than the longbow, machine gun, stealth airplane, cruise missile, and atomic bomb."[14] If successful, lasers will certainly revolutionize combat and the priorities of system design. Even

limited successes in laser weapons would likely rewrite many rules of combat. However, history suggests that any asymmetric technical advantage will be short-lived. The revolutionary potential of laser weapons is best understood in the context of the innovation, counter-innovation cycle. Ultimately, the laser weapon will become the “price of admission” on both sides of conflict for operations in a highly contested environment.

Laser Weapon Technology

While conceptually promising, a fundamental understanding of laser weapon technology is essential to realistically evaluate their future impact on air superiority and airpower projection. Understanding laser weapons, damage mechanisms, and current friendly and adversary research helps to predict the future of laser weapon systems. Ultimately, these considerations will be essential to developmental and operational planning.

Laser Fundamentals

The study of lasers, or light amplification by the stimulated emission of radiation, traces its origins to the works of Albert Einstein. In 1916, Einstein proposed a concept of stimulated emission that eventually led to the laser’s discovery.[15] In 1960, Theodore Maiman, of Hughes Research Laboratories, demonstrated the first laser using a rod of synthetic ruby.[16] At its most basic, the laser consists of three parts: the lasing medium, the power supply, and the optical resonator. Since the 1960s, scientists have continued to identify new lasing mediums, new methods of resonance, and new breakthroughs in laser types, laser power, and wavelength.[17] This discussion skims the surface of laser fundamentals, and there are many resources available to the reader for further consideration.

A basic understanding of laser fundamentals is required to understand the strengths and limitations of lasers for defense applications. The lasing material is often used to classify lasers, and it can be a gas, liquid, or solid. A pumping mechanism (e.g. electrically pumped flash lamps, diodes, or lasers, or a chemical reaction) is then used to excite the atom's electrons. As the electrons return back to a lower energy level, the lasing material releases, or emits, energy in the form of a photon. The emission of a photon can then stimulate the release of other photons causing a cascade of stimulated emission within the lasing medium.[18]

The photon, or light, that is emitted from the lasing medium behaves both as a particle and a wave that can be described by its energy, wavelength, or frequency. In order to amplify this phenomenon, the light must be reflected back through the lasing medium to stimulate further emissions of photons. For a given lasing medium and input energy level, the light emission will be at a single monochromatic wavelength. The emissions also remain in phase as they build within the lasing medium. This quality of laser light is known as coherence and, put simply, implies that the photons oscillate in unison.[19] In reality, lasers have a small frequency bandwidth of emission, and the more narrow this frequency bandwidth (higher beam quality), the longer the laser will travel while retaining its coherence.[20]

Lasers are also inherently inefficient. Much of the energy input into the laser is converted to heat because the excitation process cannot convert this energy with high efficiency. For example, fiber laser technology is the most efficient at 35 percent for solid-state (electrically pumped) lasers. Higher power is a desirable characteristic for a laser weapon, but increasing input power does not always scale to larger outputs and better results. Each lasing medium has different power limitations. For instance, heating causes a breakdown in the energy conversion

process for solid-state lasers. Excessive heating can lead to a reduced duty cycle where the laser is unavailable while it waits for the lasing medium to cool.

Diffraction, or beam divergence, is a measure of how the laser spreads out once it has left the laser aperture. Diffraction is one of the key differences between lasers and other directed energy, such as high power microwaves. A laser's low divergence is what creates the beam-like quality and the "infinite precision" attributed to lasers.[21] The diffraction itself is a function of the diameter of the output aperture and the laser wavelength. Beam divergence is minimized through larger output apertures and shorter wavelengths.[22] As the beam diverges, its power is spread over a larger area, or spot size; the power is the same, but the power density decreases. Although a laser's range is theoretically infinite, divergence is one reason that range is an important factor for laser fundamentals.

Combining together the outputs of several independent lasers can also increase laser power. The resultant beam is non-coherent in its simplest form, and the overall power is a linear addition of the input powers. When lasers are combined in phase, the coherent laser's output power is scaled exponentially. Unfortunately, combining even two beams and matching the phase is a very difficult problem.[23]

What is a Laser Weapon?

Beason defines laser weapons as "any laser used against an enemy…but generally a laser weapon belongs to a category of lasers with power levels ranging from 50 kW to over a megawatt."[24] Within the defense community, strategic laser missions typically include ballistic missile defense and long-range space (or space-relay) applications. Tactical lasers cover airborne self-defense, air-to-air combat, short-range air defense, and air-to-ground missions, among others. Lasers suffer (like many airborne capabilities) from these labels as either tactical

or strategic. Unfortunately, laser weapons are also often viewed through the unrealistic prism of science fiction as a high-tech weapon with unlimited power and application. Beginning with H.G. Wells' *War of the Worlds,* the concept of laser weapons has held a prominent role in science fiction. The fictional laser's popularity ignites the imagination, but lacks the technical constraints needed to inform prudent investment and development.

The utility of the laser has not always been clear. Even its inventor, Theodore Maiman, is quoted as saying that a laser is "a solution looking for a problem."[25] But lasers have had a role in military operations for a long time. Laser range finders, target designators, imaging, and LAIRCM each have a place in modern combat. These systems use relatively low power lasers and are not laser weapons for the purpose of this analysis. But what are the attributes of a modern laser weapon?

Perhaps the best advocacy for laser weapons focuses on their fast "speed of light" engagements, "deep magazines," scalable lethal and nonlethal force options, and low engagement costs while acknowledging their limitations and role in a larger suite of weapon systems. Rather than simply a beam of light, a laser weapon system is part of a larger employment chain like any other weapon. Laser weapon systems encompass normal functions that find, fix, track, target, engage, and assess. Each step in this employment chain is required and provides opportunities and vulnerabilities.   Like all systems, the engage step of the employment chain is driven by requirements and design characteristics. In the case of lasers, the power, wavelength, beam control, and thermal management drive design. Different applications also impose various functional and practical size and weight constraints. Finally, even the propagation to the target is a significant design element for a laser weapon system. The

following discussion helps focus on the most important design considerations and provides additional background to understand the ongoing research and development.

There are three basic categories of lasers that are receiving current investment: chemical, solid-state, and free electron lasers. Chemical lasers rely on chemical reactions to create the excited lasing medium. Chemical lasers provide many benefits and have been demonstrated in the megawatt class, but toxic chemicals create challenges for operational use. Chemical lasers received the majority of the Department of Defense (DoD) research funding through 2005, but since then solid-state lasers have dominated research with an average investment of approximately $60 million per year.[26] Solid-state lasers excite a solid material or use a doped fiber cable to generate the laser. Solid-state lasers promise a more rugged and operational design; however, the heat dissipation in the lasing material becomes a significant challenge. Depending on the solid-state medium, individual lasers have been demonstrated up to the low tens of kilowatts. Free electron lasers operate on entirely different principles accelerating light through a series of alternating magnets commonly referred to as a wiggler. Free electron lasers are wavelength tunable and scalable to high power. Free electron lasers are being researched primarily for naval or fixed ground-based applications due to the large size and weight considerations. McAulay states that free electrons lasers hold the most promise for future military applications at high power levels (multi-megawatt level) due to their tunability for diverse applications and expected cost savings.[27] All lasers take advantage of scalable power to provide both lethal and non-lethal employment options. Each of these approaches deserves continued research and provides different strengths and weaknesses in varying laser weapon applications.

The wavelength, or frequency, is a significant design consideration for laser weapons. A laser creates a monochromatic source with all energy at a nominally single wavelength. The wavelength is determined by the laser type, laser design, lasing medium, and the energy and magnetic field strength for free electron lasers. At this time, only a fixed number of wavelengths have been demonstrated based on these constraints. For atmospheric operation, the list of useful wavelengths is further constrained to operate only in certain transmission windows that allow efficient propagation (for reasons that will be discussed later).[28] Also, remember that smaller wavelengths exhibit lower beam divergence.[29] In general, smaller wavelengths are ideal for laser weapons applications.[30] But for laser weapons, the design must also consider the wavelength's interaction with the range of possible target materials.[31] Further, a singular wavelength creates vulnerabilities since countermeasures may only need to protect against the design wavelength. Wong describes free electron lasers as the "holy grail" for laser weapons due to their ability to tune their wavelength to for different applications and situations.[32]

Laser weapons are considered to have an "unlimited magazine" limited only by the chemical or electrical energy available to the system. The consumable cost of electricity, fuel, or these chemicals give lasers a low cost of engagement. Chemical lasers are limited to a fixed number of "shots" based on the quantity of chemicals available to either ground or air based applications. Electrical lasers offer more promise for "unlimited magazines." Ground-based applications can draw on grid power, generators, or batteries as "deep magazines." Airborne applications rely on airborne generators, aircraft engine power, or onboard batteries. The rate of power production and power storage capacity could limit the number of available "shots" or rate of fire. The lack of available power is another limitation that can affect the duty cycle, or availability, of a laser

weapon. Higher efficiency lasers are desirable because they require less input power, provide deeper magazines, and generate less waste heat.

For a given size and weight system, higher laser output power is generally desired. But lasers are not infinitely scalable to high power, and more electricity or larger chemical reactions do not automatically translate to higher laser output power. For example, heat dissipation remains a challenge for solid-state lasers that limits their scalability. "In a solid-state laser, even if the high power does not damage the solid [lasing] medium, it creates distortions in the medium that degrades spatial coherence and hence beam quality."[33] Higher efficiency lasers reduce input power requirements and decrease the thermal management requirements.

Beam quality is another significant factor for laser weapon systems and in many instances more important than laser power. Beam quality is fundamentally a measure of how tightly a laser beam can be focused. According to Beason, "Once a laser beam is generated, it has to be of the highest beam quality so it will have the highest intensity when it reaches the target."[34] The best beam quality has a minimum value of one, and is measured relative to a "diffraction limited" laser beam—in other words, compared against a laser with perfect optics.[35]

Lasers can also be designed for both continuous and pulsed operation; each has unique characteristics. Continuous wave lasers provide constant laser energy, create high average power, and typically heat the target. Because of the timescale for light, lasers shining for as short as one second are still considered continuous. Pulsed lasers offer the opportunity to decrease total power requirements and adjust pulse lengths.[36] Pulsed laser repetition rates vary from kilohertz to gigahertz to femtosecond laser pulse frequencies. McAulay even describes situations in which the "light from a pulsed laser can look like a light bullet."[37] These high power pulsed lasers can be used to drill holes in ceramics.[38] In some instances, damage

mechanisms for laser weapons may yield better results with either pulsed or continuous wave systems. For instance, according to an Air Force-sponsored National Research Council (NRC) workshop, "pulsed lasers may be the only effective [laser weapon against] the more advanced class of adversary SAMs (double-digit SAMs)."[39] No doubt both pulsed and continuous wave lasers will have roles in future laser weapons.

The ability to find, fix, track, target, and engage the adversary also creates challenges for laser system design. Multiple sensor technologies can be integrated into a laser system—radar, infrared, laser, or other future technologies. The primary consideration is to meet the requirements for identifying targets and then providing the fidelity to maintain a highly precise spot on the target. Although the laser operates at the speed of light, the laser spot must be held on the target with enough dwell time to meet lethality requirements. To maintain this level of precision, the platform stability and beam control must meet stringent requirements. Research remains ongoing to continue to improve and integrate these technologies for future systems. As this paper will develop, these sensors (and their vulnerabilities) will have a major role in the upcoming cycle of innovation and counter-innovation.

The laser's challenges do not end after it is fired. Absorption, scattering, and turbulence all degrade laser propagation through the atmosphere. The impacts on lasers vary because of the relationship between the atmosphere and altitude. Water vapor, pollutants, and other particles in the air, which are more prevalent at lower altitudes, cause absorption and scattering. These particles also interact with the laser's wavelength and limit the laser's propagation in certain frequency bands. Overall, lasers fired at high altitude have much longer propagation ranges compared to low altitude shots. Turbulence in the atmosphere also impacts laser propagation in relation to the laser wavelength and the range to the target.[40] For lasers weapons, turbulence

generally refers to convection from vertical temperature differences, wind shear, and the micro-scale random motion of air in the atmosphere (at the scales from 2mm to 200m).[41] The turbulence breaks up the laser beam and reduces the power delivered over longer ranges.[42] For airborne platforms, additional turbulence and the aircraft flow-field also present challenges. Weather complicates laser propagation beyond the basic atmospheric effects and will be discussed later in this analysis.

Thermal blooming is another degradation that can effect the laser's propagation. If the laser is held stationary through the same air pathway, the laser heats up the air and distorts the beam causing "thermal blooming" phenomena. If the laser weapon is stationary (e.g. ground-based point defense), thermal blooming presents a greater challenge because the beam is more likely to be held stationary through a single path of air. In contrast, thermal blooming is less likely in moving airborne engagements; however, certain engagement geometries are still affected.

As a result of these challenges, many have argued that beam control may be the toughest challenge for laser weapon development.[43] But adaptive optic technology continues to improve. Adaptive optics offer the opportunity to compensate for much of the distortion that occurs in the atmosphere, but it comes with the cost, weight, and complexity of additional optics. Ongoing research from the Defense Advanced Research Projects Agency (DARPA) is also examining optical array technology with the target-in-the-loop to achieve "near-perfect compensation for atmospheric turbulence."[44]

Lethality and Damage Mechanisms for Laser Weapons

Understanding the laser weapon's damage mechanism, or lethality, against a range of military targets is essential for determining the laser's utility in military applications. Not only are the laser power, beam quality, and propagation character essential, the ability of the laser to

create an effect on the target must be understood. In comparison to other weapons, lasers offer extreme precision, and the power or aim point can be modified to achieve both lethal and non-lethal effects. This flexibility and the laser's natural characteristics provide both advantages and disadvantages for lethality.

Before discussing any target sets, damage must be discussed in terms of effect on the target, or lethality. This effect is a function of both the energy delivered and the time on target. Fluence is a measure of the energy absorbed into the target. Perram describes the interaction of the laser and the target in four basic stages:

> 1) the absorption of laser radiation by the target materials; 2) the redistribution of the energy into various material responses such as heating, radiation, and ablation; 3) the response of the material such as thermal penetration, rupture, and fracture; and 4) response of the system as a whole[45]

The laser wavelength plays a key function in the energy delivered to the target based on the interaction, or coupling, between the laser and target material.[46]

"Power in the bucket" is a common method used to compare laser weapons because of its traceability to lethality. The bucket is the diffraction limited "spot" on the target, and the method evaluates the time-averaged energy delivered against this "spot."[47] The longer and more tightly that the laser weapon is kept focused, the greater the laser's time on target and the greater the total transfer of energy into the target. Higher power lasers decrease the dwell time required to generate the desired effects and reduce the time available to laser countermeasures. Although the engagement occurs at the speed of light, the dwell time required to create effects (typically desired to be on the order of one to five seconds) still means that a target's closing speed and maneuverability matters.

The Air Force continues to conduct lethality research: developing a lethality database, lethality models, and "laser vulnerability experiments on materials, components, and targets."[48]

Specific lethality results against real-world targets are classified, which makes comparison and evaluation of competing technologies difficult. However, the physical damage mechanisms for laser weapons can be identified. Damage mechanisms vary depending on the target properties and whether the intent is to deny, degrade, damage, or destroy the target. The target materials drive how laser energy is absorbed, how the energy is redistributed within the target, and how the material responds.[49] Target vulnerability is highly variable and requires detailed intelligence and knowledge about the target's systems and subsystems. Damage mechanisms may include melting or cutting, structural failures, or igniting combustible components. With increased rates of total heating, the laser may cause material expansion, property changes, melting, vaporization, ablation, spalling, or even plasma.[50] At lower power levels, more sensitive components can be dazzled (blinding using a matched wavelength) or crazed (creating crack-like damage to optics).

Specific lethality estimates were not considered for this research due to classification concerns; however, the continued investment in laser weapons reveals that lethality estimates remain promising. The following open source anecdotes provide a sample of government and industry results from lethality testing. By 1984, the Airborne Laser Laboratory (ALL), a modified Boeing NKC-135 with a 400 kW laser, conducted five intercepts against AIM-9 air-to-air missiles.[51] Laser weapons have also demonstrated the ability to blind the guidance systems of air-to-air missiles.[52] In 2003, analysis on the utility of a "HEL Fighter" (high energy laser) stated "a majority of airborne and ground-based military targets, including infrared and radar anti-aircraft missile threats are vulnerable to lasers."[53] During airborne testing in 2010, the Airborne Laser (ABL) heated the target ballistic missile's surface using laser energy during the launch phase and exploited the missile's internal hoop stress to destroy the missile.[54] In 2010, Dan Wildt, Vice President of Directed Energy Systems for Northrop Grumman, stated "We have been

demonstrating laser performance at HELSTF [High Energy Laser Systems Test Facility] and other test sites for many years, unequivocally proving their lethality against a wide variety of potential threats" including various missile types, helicopters, unmanned aerial vehicles (UAVs), rockets, artillery, and mortars. [55] The Defense Threat Reduction Agency (DTRA) and Science Applications International Corporation (SAIC) see ultrafast pulsed lasers in a game-changing role in the counter-sensor mission disrupting electro-optical and infrared sensors.[56] McAulay also suggests that high power pulsed lasers could even generate plasma that "can reportedly interfere with jet engine intakes" or even help focus microwave frequencies.[57]

Even the target aspect matters for lethality estimates. The laser's aim point on the target is crucial, and different target aspect angles expose or protect different aim points. The Department of Defense Laser Master Plan from 2000 illustrates the importance of target aspect for an airborne engagement:

> It is more difficult to destroy a missile that is heading nose-on to the beam because the nose can be made hard to radiation. It is much easier to destroy a missile that presents more of a broadside view to the beam, since it is then possible to place the laser energy on the most vulnerable part of the missile.[58]

The head-on target aspect is most often encountered in a point defense or self-defense scenario where the laser is aimed outward at an incoming weapon. Additionally, these "head-on" shots are more likely to create thermal blooming, which degrades the laser's effectiveness as previously discussed. For Naval applications, the Congressional Research Service (CRS) reports that a "head-on" self-defense engagement against an Anti-Ship Cruise Missile (ASCM) is likely to require a 1 MW laser. In contrast, a 300 to 500kW laser would be sufficient against a crossing ASCM in an area defense role (enabling a broadside shot).[59] The increased vulnerability of crossing targets and the concept of area defense retains merit for airborne engagements. Area defense or "buddy" defense involves multiple mutually supporting lasers operating as a group.

Tactics keep the group in close proximity (relative to the laser's range) to allow mutual support. In an area or "buddy" defense scenario, each laser weapon views the target from a different aspect, potentially gaining an advantage.

The final aspect of the kill chain is to assess the effects of the engagement—whether or not lethality was achieved. The laser's flexibility adds challenges to this assessment. Certainly, some damage mechanisms will have immediately obvious effects on the target such as exploding a fuel tank, detonating an explosive payload, or cutting off the wing of a small UAV. However, other damage mechanisms against sensors, optical components, or electronics may have much less notable effects. But yet, the ability to confidently assess a laser's effects on the target is essential. Whether or not the desired effects have been achieved is often only a function of dwell time, and accurately identifying the "kill" and then quickly moving on to the next target will play a major role in a dynamic combat situation with multiple targets. Before lasers fully emerge onto the battlefield, the ability to accurately assess damage requires additional research. The Air Force recognizes this need and, according to FY15 budget documents, is currently pursuing "kill assessment technologies."[60] Ultimately, a full understanding of lethality and the ability to assess its effects will be essential to the operational employment of laser weapons.

Recent Research and Development for Laser Weapons in the DoD

In the Department of Defense, laser weapon research is not new. Ever since the first laser was created in 1960, the military has pursued laser technology and military applications. During the Cold War, the large size, heavy weight, and high costs of "state-of-the-art" laser weapons focused efforts on "strategic" applications. But the desire for "tactical" laser weapons never faded. There have been tremendous successes and advances in laser weapon systems over the past half-century and understanding the current state of research and development is necessary to

inform future projections. This review focuses only on the most recent advances in laser weapons, which includes integrated development of laser systems and supporting technologies. For those that are interested, there are now many sources available that provide additional background on early laser weapon programs in the DoD.

In September 1999, the DoD conducted a study that focused on chemical lasers, solid-state lasers, free electron lasers, beam control, lethality, and other advanced directed-energy technologies. [61] The study mirrored the analysis in the Laser Master Plan for the DoD. [62] Both studies reinvigorated the research into high-energy lasers (chemical, solid state, and free electron lasers). These studies already concluded that HELs were ready for both offensive and defensive applications. The studies suggested that laser weapons provided a potential area for the United States to maintain an asymmetric technological advantage. Further, they laid the groundwork for additional research and the creation of the High Energy Laser Joint Technology Office (HEL-JTO) in 2000. The HEL-JTO was arguably the first joint office established to advocate and develop a specific new weapon technology.[63] While the office's legacy is still undecided, these actions certainly renewed emphasis on laser weapon research.

In 2007, the Defense Science Board Task Force on Directed Energy Weapons concluded that "the range of potential applications is sufficient to warrant significantly increased attention to the scope and direction of efforts to assess, develop, and field appropriate laser, microwave, and millimeter wave weapons."[64] Based on advancements in laser technology, this study refocused research and development on solid-state lasers, fiber lasers, and beam control.

Since 2000, the Airborne Laser (ABL) provided the most public image of laser research. In February 2010, the ABL successfully shot down a solid-fuel Terrier Black Brant rocket.[65] Later that February, the ABL successfully engaged a liquid fueled tactical ballistic missile (TBM)

during the boost phase using "50% less dwell time than expected to destroy the missile."[66] Within one hour of the first engagement, a second was attempted against a solid-fuel rocket but the engagement was cut short due to a "beam misalignment" problem.[67] The ABL program was cancelled in 2011. Then-Secretary of Defense Robert Gates told Congress that the ABL's projected lethal range was only 85 miles (137 km) and did not offer the range needed for boost-phase missile defense.[68] However, the cost and reliability were the major detractors, and the Missile Defense Agency (MDA) is still pursuing similar capability.

The Joint High Power Solid State Laser (JHPSSL) program was a major initiative of the HEL-JTO and created significant breakthroughs in solid-state laser technology. During the JHPSSL Phase 3, Northrop Grumman demonstrated a 105kW laser made up of seven diode-pumped Vesta lasers. Northrop Grumman's Vesta design relies on modular 15kW lasers with beam quality of 1.3 times the diffraction limit (DL).[69] Northrop Grumman now advertises the FIRESTRIKE laser based on the technology from earlier Vesta and Vesta II lasers. The FIRESTRIKE is advertised as a rugged and scalable line replaceable unit (LRU), 15kW power, beam quality of 1.5 DL, continuous operation reaching full power in less than one-half second, at a weight of 400 pounds (laser LRU only).[70] At present, the FIRESTRIKE is advertised as scalable to 120kW with higher power possible.

Both government and industry-sponsored demonstrators began to showcase the potential laser applications as breakthroughs occurred in solid-state laser design. Ground-based system demonstrators are most common because of the less rigorous size and weight constraints. The High Energy Laser Mobile Demonstrator (HEL MD) mounts a solid-state laser on a customized Heavy Expanded Mobility Tactical Truck (HEMTT).[71] In 2008, Boeing developed the HEL MD as a point defense system against rockets, artillery, mortars, and UAVs. The design is intended

to provide a rugged, mobile prototype, and "as technology matures … to extend range and increase system effectiveness."[72] The HEL MD uses a 10kW laser with future iterations planned at 50kW then 100kW. Dexter Henson of Boeing commented, "Not only does it work, it works with a 10 kW laser. We [Boeing] surprised some people with the capability of a 10 kW laser."[73] Thermal management is provided by a two-loop chilled water system, which adds size and weight to the system.[74] The system uses infrared acquisition and tracking and a 300W target illuminator laser.[75] The Army's Space and Missile Defense Command (SMDC) hopes to see the HEL MD deployed sometime between 2019 and 2024.[76]

In fact, with DoD cooperation, the HEL MD is already slated for integration into the air defense network in Israel. In 2014, Israel's Rafael unveiled the IRON BEAM system that offers a directed energy layer to supplement air defenses. The planned system is based on the High Energy Laser Weapon System technology from Boeing and the United States Army's HEL MD. The IRON BEAM uses solid-state laser technology and is focused on close-range air defense in a counter rocket, artillery, and mortar (C-RAM) and counter-UAV role.[77]

Raytheon provides a similar system for ground-based air defenses. The Raytheon technology uses a different solid-state "planar waveguide" structure for its high-energy laser that they project will scale to over 200 kW.[78] The result is a "high quality beam projected to reach 1.2 DL and over 38% efficiency."[79]

Lockheed Martin also developed a short-range air defense system based on fiber laser technology. The Area Defense Anti-Munitions (ADAM) is a ground-based, transportable system to provide short-range air defense.[80] ADAM was developed using a commercial 10 kW fiber laser.[81] The system's effective range against airborne rockets and UAVs is reported as 1.9 km.[82] Lockheed has conducted multiple tests to demonstrate performance and advertise potential

applications. Since 2012, the ADAM system was demonstrated against UAVs,[83] Qassam-like rockets,[84] and the rubber hull of military-grade small boats.[85]

Fiber laser weapon systems have gained increased attention as fiber technology caught up with other solid-state laser designs. As of March 2014, Lockheed Martin demonstrated a record-setting 30kW fiber laser with high electrical efficiency and beam quality.[86] Under the Accelerated Laser Demonstration Initiative (ALADIN) for the United States Army, Lockheed is contracted to provide a 60 kW laser in 2017 and a 100 kW laser in 2022.[87] Lockheed claims their fiber laser technology is "fundamentally scalable" beyond 100 kW.[88] Rob Afzal, senior fellow for Lockheed states that, "[Fiber lasers] offer the highest efficiency at high power, routinely over 30 percent; fantastic beam quality, which puts more intensity on target at longer range; and are the most affordable, because component technology is being advanced by the industrial laser market."[89] Lockheed combines the beam using a technique called spectral beam combining, which "sends beams from multiple fiber laser modules, each with a unique wavelength, into a combiner that forms a single, powerful, high quality beam."[90] In March 2015, Lockheed announced successful demonstration of the 30-kW laser design against a representative target. According to the press release, the Advanced Test High Energy Asset (ATHENA) used the ALADIN laser to "burn through the [truck's] engine manifold in a matter of seconds from more than a mile away."[91]

The advances in commercial lasers are also providing direct benefits to laser weapon research. High power lasers have commercial applications in welding metal, cutting steel, drilling through rocks, and fiber communications.[92] Military lasers generally drive much higher beam quality requirements (for long range application), but the widespread commercial use is increasing the availability, affordability, and power levels for solid-state and fiber lasers. For

example, fiber lasers are heavily used in the drilling and welding industry with rapid technology advances and now 1 to 10kW lasers are commercially available, albeit with lower beam quality.[93] The CRS considers fiber lasers a "very robust technology" and states that fiber lasers are "widely used in industry—tens of thousands are used by auto and truck manufacturing firms for cutting and welding metal."[94]

The United States Navy's new Laser Weapon System (LaWS) is an excellent example of the synergy gained from commercial development. The LaWS is mounted on an Mk 15 Phalanx Close-In Weapon System (CIWS) and expected to counter a spectrum of threats at short range including: UAVs, missile seekers, Intelligence Surveillance Reconnaissance (ISR) systems, rockets, MANPADS, mortars, floating mines, and artillery rounds.[95] With a total power of 32.4kW, LaWS leverages technology from lower cost, commercially available 5.4kW fiber optic lasers.[96] Beam quality for the LaWS is 17 DL,[97] still relatively low compared to other prototype systems. The LaWS is 25% efficient[98] requiring approximately 120kW of ship power to operate. The six laser beams are not combined, but rather converge simultaneously at the target to create a similar effect. The LaWS effective range is reported as 1.6 kilometers.[99]

In 2013, the USCENTCOM initiated the Solid State Laser Technology Quick Reaction Capability (SSL-QRC) to upgrade the LaWS for deployment.[100] The LaWS was installed on the *USS Ponce* and deployed to the 5th Fleet in the Persian Gulf in August 2014.[101] *Wired* magazine concludes that the LaWS capability provides a direct counter to Iran's unmanned surveillance and "swarming fast-boat tactics."[102] A "Lasers for Naval Application" budget justification states that solid-state lasers provide the "ability to deter, damage and/or destroy asymmetric threats including rockets, missiles, fast attack craft, and Unmanned Aerial Systems (UASs)."[103] According to these same documents, research "at the unclassified level… will provide the

capability to dazzle ISR sensors at tactically significant ranges."[104] Rear Admiral Klunder, USN Chief of Research, highlights the economic argument driving the LaWS urgency, arguing that laser energy engagements will cost about one dollar compared to the cheapest conventional defenses beginning at $5,000 per engagement[105] and a still relatively inexpensive SM-2 engagement priced at $400,000 per missile.[106] According to the CRS, the cost of adding a production LaWS to the CIWS platform is estimated at $17 million per system.[107] The potential for cost savings is evident even with the additional sunk cost of the laser.

The Defense Advanced Research Projects Agency (DARPA) is leading research on airborne laser applications with multiple programs ongoing. DARPA laser programs include: High Energy Liquid Laser Area Defense System (HELLADS), Excalibur, Endurance, Flash, and Aero-Adaptive/Aero-Optic Beam Control (ABC). Gizmodo captures the spirit with its recent lead-in, "DARPA is going gaga over the pew-pew."[108]

Most prominently, DARPA developed the HELLADS laser system, which is a small (less than 2000 lbs) but powerful laser. The General Atomics laser combines the "high-energy density of the solid-state laser with the thermal management of liquid lasers."[109] The goal of the HELLADS program according to DARPA is:

> To develop a 150-kW laser weapon system that is ten times smaller and lighter than current lasers of similar power, enabling integration onto tactical aircraft to defend against and defeat ground threats. With a weight goal of less than five kilograms per kilowatt, and volume of three cubic meters for the laser system, HELLADS seeks to enable high-energy lasers to be integrated onto tactical aircraft, significantly increasing engagement ranges compared to ground-based systems.[110]

The 150 kW laser has been delivered and checked out in the laboratory, and the "integration and subsystem testing of the ground-based demonstrator laser weapon system" was completed in 2013.[111] The FY14 budget plan included prosecuting "live fire targets from a mountain peak test

site to demonstrate the performance of the laser weapon system in airborne missions to include targeting of ground vehicles and self-defense against SAMs."[112]

DARPA and the Air Force plan to use the HELLADS to demonstrate laser weapon applications in the Electric Laser Large Aircraft (ELLA) program. According to an Air Force Research Laboratory (AFRL) Request for Information to industry:

> The ELLA program is a program to develop, integrate, and demonstrate high power electric laser weapon technologies to meet [Air Force] capability needs in limited airborne tactical precision engagement (air-to-ground) and self-defense (air-to-air) applications. The program's end goal is the demonstration of the technical maturity, capabilities, characteristics, and lethality of a laser weapon system at a level that will support transition to a future system acquisition program of record.[113]

This program envisions a B-1B demonstration against air-to-air and air-to-ground targets.[114] The "third-generation" Laser Weapon System Module (LWSM) mates the laser into a B-1B bomb bay.[115] According to a 2013 National Research Council (NRC) workshop, "a HELLADS Demonstrator Laser Weapon System (DLWS) with 150 kW output is now complete."[116] Ground tests of the HELLADS laser were projected to begin at White Sands Missile Range in 2013 and to be followed by integration onto a B-1B for airborne tests.[117] One of the long-term objectives for the airborne LWSM is to target an adversary integrated air defense system.[118]

The Robust Electric Laser Initiative (RELI) program is considered a "second-generation" HELLADS system.[119] As of 2013, RELI was a primary focus for the HEL-JTO.[120] Under the RELI program, Northrop Grumman used fiber laser technology to match JHPSSL performance while increasing efficiency to over 30% and maintaining beam quality.[121] Northrop Grumman claims 25 kW, 50 kW and 100 kW fiber laser systems have been demonstrated with coherently combined beams. The Air Force budget exhibits for FY15 show that the RELI program is continuing work to build both a 60 kW and 30 kW laser source "for integration on relevant

military platforms."[122] The size and weight of the RELI laser system is "small enough to enable it to be carried under a Predator C Avenger RPA (the HEL Avenger concept), and its output power is about 100 kW."[123] The NRC report cites a $20M unit cost for the HEL Avenger laser system.[124] These fiber lasers show great promise for airborne applications.

Also under DARPA, the Excalibur program seeks to develop a system using fiber lasers and coherent optical array technologies that allow multifunction "laser radar, target designation, laser communications, and airborne-platform self protection tasks."[125] DARPA summarizes the advancements made in the Excalibur program as follows:

> Excalibur provided the technology foundation for defense of next generation airborne platforms, including all aircraft flying at altitudes below 50,000 ft, against proliferated, deployed, and next-generation man-portable air-defense systems (MANPADS) and more capable air-to-air missiles converted for use as ground-to-air missiles.[126]

The program expects that it will be able to create an approximately 100 kW laser system[127] in the next three years.[128] Earlier in the program, Optonicus (the contractor) used a phased-array design to overcome challenges in "long-range turbulence correction and scalability" for optics.[129] The newest system design consists of 21 individual elements and is able to "correct for atmospheric turbulence within a millisecond."[130] *Optics and Photonics News* states that the Excalibur array has "high power efficiencies of 35 percent and near-perfect beam quality, [and] was used to precisely hit a target more than 6.4 km away."[131] Excalibur also investigates laser beam steering technologies that could allow more conformal rather than turret based laser systems.[132] DARPA budget exhibits explain further, "Excalibur arrays are conformal to aircraft surfaces and scalable in size and power by adding additional elements to the array."[133] The evolution of fiber amplifiers was a significant breakthrough for laser weapons, such as Excalibur. According to an NRC workshop in 2013, "The DARPA program is currently achieving the

5kg/kW [weight goal] for the Excalibur laser system mounted on a Reaper RPA [remotely piloted aircraft]…[using] eight 3-kW fibers in the laser array."[134]

Project Endurance is a DARPA spin-off from the Excalibur program focused on miniaturization, high precision target tracking, lightweight beam control, target interactions, and threat vulnerabilities; the stated goal is a pod-mounted laser system.[135] The project is currently being pursued by Northrop Grumman to develop podded, miniaturized defensive lasers for airborne platforms to defeat electro-optical and infrared (EO/IR) guided surface-to-air missiles.[136] In order to meet these requirements, the laser's output power is roughly 30 to 50 kW.[137] Similar to the Excalibur program, the system used reflected energy from the target to individually tune 3-kW fiber lasers, which each operate at 35% "wall-plug efficiency."[138] DARPA states in its FY15 budget that the system is designed to defeat emerging and legacy EO/IR missiles, and in 2014, DARPA funded requirements to acquire threat representative devices for testing.[139] The earliest that the Endurance program might be ready to transition to an operational capability is in 2018.[140]

The FY15 DARPA budget reveals another related program line for a fiber laser weapon system—Flash, "Scaling Fiber Arrays at Near Perfect Beam Quality."[141] According to these budget documents, the goals of Flash are "to demonstrate array combinations of ultra-lightweight high-power fiber lasers that project 100 kW-class beams with near-perfect beam quality and very high … efficiency."[142] Reaching beyond the goals from HELLADS, "the technical objective is to achieve ultra-low SWaP [size, weight and power] at 2 kg/kW specific power and a size of 1m^3 per 100 kW."[143] Potential applications range from tactical to long-endurance aircraft. DARPA's plans for FY14 included "demonstrating an array of ~1.2 kW fiber-lasers combined to produce over 30 kW near-diffraction-limited output at over 30% electrical-to-optical efficiency…and

demonstrating target-in-the-loop phase-locking on stationary and moving extended targets at 1 to 8 km tactical distances."[144] Long-term, Flash is "focused on defeating EO/IR guided air-to-air missiles, as well as surface-to-air missiles, with a beam power of up to 300 kW."[145]

DARPA's ABC program is also currently advancing required supporting technologies for airborne laser systems. The program is investigating flow control and optical compensation technologies with 360-degree coverage for military aircraft.[146] According to DARPA, "High-energy laser systems are currently limited to a forward field of regard due to turbulent density fluctuations in the aft sector of the turret that severely degrade the laser beam fluence on target."[147] As of 2014, work continued on turbulence encountered in the aft hemisphere. The program further seeks to integrate flow control and adaptive optics technologies for even greater performance and compensation over longer ranges.[148] In total, DARPA's programs continue to advance the "state-of-the-art" for airborne laser applications.

In addition to the work on smaller "tactical" airborne applications, the pursuit of a "strategic" follow-on to the ABL continues. According to the FY15 budget for the Missile Defense Agency (MDA), "MDA is pursuing the Diode Pumped Alkali Laser System and fiber combining laser technologies based on their efficiency and scaling potential. A 200 kilowatt (kW) class flight-qualifiable laser prototype will be built and tested."[149] In 2013, vibration instrumentation flight tests were flown on the Phantom Eye UAV.[150] The budget justification continues that "a surrogate high-altitude, long-endurance platform will be instrumented to collect high-altitude flight environment data to inform the design and flight compatible packaging of the high powered laser payloads."[151] The successes in research and development for both tactical and strategic-class laser weapons suggest a range of future potential applications.

As of 2014, Broad Agency Announcements from the HEL-JTO suggest that technology research efforts continue on: free electron lasers, solid state lasers [including fiber lasers], beam control, and battle damage assessment studies for directed energy counter-ISR.[152] As research continues over the next decade, the goals will still include: increasing beam power, maintaining or improving beam quality, improving beam efficiency or thermal management, improving beam control, and ruggedizing the systems to meet warfighter needs.

Foreign Trends in Laser Weapon Development

Laser weapon developments in the United States have been significant, but what is the state of laser weapon research around the world? Innovation and counter-innovation—foreign competition—in laser weapon development is not new. The United States and the Soviet Union both aggressively pursued laser technology throughout the Cold War. Globalization and the worldwide proliferation of technology are now making advanced laser technology more accessible. The laser's heavy commercial use also drives proliferation. The Air Force Chief Scientist outlines this proliferation trend broadly, but it applies to laser technology as well:

> The increasing proliferation of technologies as well as the increasing availability of commercial components for innovative or traditional use in systems, will shorten the foreign research, development, acquisition, and deployment timelines, meaning advanced capabilities will be reaching military systems in a reduced time frame.[153]

In 2007, the Defense Science Board Task Force warns that, "The development of …technologies and systems available to potential adversaries poses a new set of challenges to U.S. military force capabilities."[154] According to research by the CSBA, the desire to counter the United States' advantages will drive foreign laser development.[155] Commercial and adversary indigenous laser development provides the means to counter the United States' sensor and precision network.

The CSBA expands that adversary advancements will also promote further laser research in the United States. The CSBA cautions that, "to overcome the barriers [of implementing directed energy weapons], it may take a catalytic event such as a directed energy breakout by an enemy before the U.S. military fully grasps that these weapons have become reality."[156] These foreign advances warrant concern. At this point, the United States maintains the lead in laser weapon development, but others countries will continue to make progress, particularly for ground-based defensive systems. The National Research Council summarized the conclusions of the military's 2009 Directed Energy Net Assessment:

> The analysis indicated that Red Force defensive DEW capabilities including both HPM [high power microwave] and HEL [high energy laser] systems, could substantially compromise the effectiveness of Blue Force air attacks. From the modeling and simulation of representative scenarios, the conclusion was that Red Force integrated air defense system infused with DEW defensive anti-air systems poses a significant risk to Blue Force strike mission success.[157]

The following open source evidence demonstrates advancements, development, and proliferation of laser weapons around the world.

Like the Untied States, Germany has also conducted laser weapon research. The German company, Rheinmetall, has been gradually increasing laser power in a series of tests at the Ochsenboden proving grounds. Rheinmetall's high-energy laser uses two diode-pumped solid-state lasers.[158] By 2012, Rheinmetall had mounted a 10kW laser on an existing air defense platform with a SKYGUARD 3 fire control unit and SKYSHIELD gun turret.[159] In November 2012, Rheinmetall improved to a 50kW design using "Beam Superimposing Technology" to combine together two lasers rated at 20kW and 30kW.[160] Testing was demonstrated against three representative targets. First, the beam cut through a 15mm steel girder at 1 km distance. Second, the beam shot down a UAV at a range of 2 km. Third, an 82mm steel ball was destroyed in a simulated mortar attack.[161] The German company also claims that weather was a

factor during testing, but the system operated successfully even in bad weather.[162] Rheinmetall aims to build a 60kW laser next and believes the 100kW power level is feasible.[163]

China is also researching and developing laser weapon technology. Although there is not much open-source information available, it is commonly assessed that China is pursuing directed energy technologies. *Defense Today* highlights the abundance of unclassified publications and scholarly journals focused on basic laser weapon technologies, beam directors, and related technologies.[164] The integration of these basic technologies and current capability of these systems is largely unknown. Kopp suggests that, "the PLA [People's Liberation Army] will be a major player and we can expect point defense applications such as counter-PGM [precision guided munition] and counter-cruise missile systems to be the first to emerge, as the power, beam quality and pointing requirements are the least challenging."[165] The DoD has also stated that China appears to be developing ground-based lasers for an anti-satellite role. In 2006, the National Reconnaissance Office (NRO) Director confirmed that China had illuminated an American satellite using a ground-based laser.[166] The past Chinese research focused heavily on chemical lasers similar to the United States, but more recent efforts have shifted to solid-state and fiber laser technology. In November 2014, China's Academy of Engineering Physics unveiled an indigenous 10-kW laser weapon system designed to target UAVs.[167] China claims that the laser, the Low Altitude Sentinel System, is capable of targeting small UAVs within 5 seconds of identification, at altitudes up to 500 meters above the ground, ranges up to 2 kilometers, and speeds up to 50 meters per second.[168] China's Academy of Engineering Physics also confirmed that laser systems with greater power and range were in development.[169]

Russia is also researching and developing laser weapon technology. During the Cold War, the Soviet Union had a robust laser program with research ranging from space-based to

battlefield laser weapons.[170] While interest waned after the fall of the Soviet Union, recent evidence suggests that Russia may have renewed interest in laser weapons, and directed energy more broadly.[171] Former Chief of the Russian General Staff, Yury Baluevsky, claims that Russia is on a path similar to the United States in laser weapon development, to include airborne lasers.[172] In 2009, evidence showed new life for the Russian A-60 "Falcon-Echelon," an Ilyushin-76 equipped with a laser weapon.[173] This Russian laser weapon is reported to be a megawatt-class laser designed to target satellites with other airborne applications under consideration for the future.[174] However, other statements also make it clear that Russia is experiencing similar issues with laser power and beam propagation.[175] Russia is also pursuing countermeasures to laser weapons. For instance, Lexington Institute reports that, "Russian SS-27 ICBM [Intercontinental Ballistic Missile] is reported to have incorporated a number of countermeasures to directed-energy weapons, including reflective coating and booster rotation."[176] Most likely, Russia is conducting more laser weapon research activity beyond these open source revelations.

The Indian Ministry of Defense also highlights directed energy weapons as a top priority through 2025 in its Technology Perspective and Capability Roadmap.[177] India identified this technology as a game-changer and part of a global shift to "non-contact wars" of the future (alluding to the laser's scalable effects).[178] In 2010, India's Aditya program was focused on achieving the 100kW power level from a vehicle-mounted gas-dynamic laser.[179] Overall, India is pursuing lasers from 100kW to 1MW to fill both tactical and ballistic missile defense capability gaps but acknowledges that significant technical challenges remain.[180]

Turkey also recently joined the list of countries pursuing indigenous laser weapon systems for short-range point defense. In 2015, Turkish officials confirmed the first tests for a prototype laser system that successfully destroyed its intended target.[181]

The large numbers of countries that are experimenting with laser weapons makes further advances and proliferation likely. The United States must be prepared to operate against laser weapons in future highly contested environments.

Laser Countermeasures and Skeptics

Like any other weapon system, laser weapons have limitations. Similarly, it is inevitable—countermeasures and counter-countermeasures will be developed for laser warfare. But with an understanding of the cycle of innovation and counter-innovation, these concerns should inform future weapon designs but not stop investment. The following discussion will analyze potential countermeasures and the limitations of lasers to illustrate this point. Advanced countermeasures and weapon vulnerabilities are highly sensitive; therefore, only general techniques from open source materials have been considered. As research into laser weapons continues, a deeper understanding of potential countermeasures and limitations will require continued funding. Technology and tactics will work through many limitations, but countermeasures will have the greatest long-term implications on role of lasers weapon in 2045.

What do laser countermeasures cover? Laser countermeasures are methods used to deny or degrade the effectiveness of laser weapons. The investigation of laser countermeasures seeks to understand: 1) how the United States' laser weapons could be undermined by an adversary, and 2) how the United States could negate the effects of an adversary's laser weapon. These limitations and vulnerabilities are a significant concern and appropriately veiled in secrecy. Several offices throughout the DoD are investigating laser countermeasures and vulnerability to

laser weapons. Fortunately, the long life of military equipment suggests that the United States will continue to face legacy equipment that is susceptible to laser weapons and will not contain laser countermeasures. Further, any new or retrofit countermeasures add cost and complexity for the adversary. The countermeasures below are discussed in terms of passive and active countermeasures that either focus on target survivability or disrupting the laser's kill chain.

Passive countermeasures provide continuous defense against threat systems and are best implemented during system design. These passive countermeasures can be based on the target or the kill chain to deny laser lethality or degrade the laser's effects. Potential passive countermeasures include thermal coatings, reflective surfaces, ablative surfaces, or hardened material such as ceramics. The FY15 Air Force budget exhibits show that research continues on advanced materials to protect aircrew, sensors, and aircraft systems.[182] The technologies include hardening, coatings, and damage-limiting technology.[183] Similarly, the Office of Naval Research evaluates the ability to dissipate, defocus, and reflect energy by taking advantage of "transmission and conversion inefficiencies."[184] Each potential countermeasure has technical strengths and weaknesses based on the laser design choices such as: wavelength, power level, and whether the laser is continuous or pulsed. For example, since the coupling between a laser and the target material is a function of wavelength,[185] countermeasures will likely be tailored to block or protect against known laser wavelengths. As a result, these countermeasure technologies (tuned to specific wavelengths) are likely to drive laser war reserve modes for available wavelengths and continued interest in tunable wavelength lasers. As another example, the Lexington Institute points out that, "Shielding or ablative material can attenuate the effectiveness of continuous-wave laser weapons but will be relatively ineffective against pulsed lasers that use impulse power as their damage mechanism rather than target heating."[186]

As passive countermeasures, these approaches generally increase the time required for an engagement but still leave the target vulnerable. However, increased engagement time is still a significant countermeasure that forces longer dwell time or higher power levels from the attacker. During tests supporting the ABL, researchers at Phillips Lab conducted lethality testing by investigating the use of a highly reflective missile body as a countermeasure. The results showed that highly polished, painted and unpainted, surfaces still absorbed lethal amounts of laser energy.[187] The Air Force continues to work on these countermeasures. To this end, the Air Force is also conducting a hardening assessment for airframes and anti-access munitions to determine the effects of laser weapons.[188]

Since it is unlikely that a target can be fully hardened against laser energy, tactics may offer a means to overcome these passive countermeasures. For instance, a ground or airborne "point defense" or self-defense laser may only have a head-on shot against an incoming missile. If that missile's nose cone is hardened against laser energy, the dwell time could be significant—denying the laser effect or increasing vulnerability to swarm tactics. However, cooperative "area defense" or buddy-defense tactics could overcome this countermeasure. In this example, a geographically separated "buddy" laser would have a different, more lethal aspect to the incoming missile.

Passive methods such as stealth or low-observable technology also offer a countermeasure against laser weapons. If the laser system cannot find and identify targets, the laser has no utility. However, the advancement in both passive and active ISR sensors suggests that low-observable technologies may be less assured in the future. In 2045, this paper assumes that delaying detection may add value, but avoiding detection will be impossible.

For any active countermeasure system to be effective, the first step is to recognize the attack. Laser warning devices exist today and are assumed to also meet future requirements. McAulay states that the “challenge is to detect the threat laser light fast enough for the target to evade the threat beam or launch countermeasures to save the target.”[189] It is redundant to point out that lasers create effects at the speed of light, but time is still available for countermeasures. Active target identification or laser weapon fire can be detected, and a reaction initiated. Further, the dwell time for lethality offers a few seconds for a countermeasure reaction. Two broad categories require further discussion: maneuver and direct counters against the threat laser system.

For maneuver countermeasures, targets can employ steady-state spin or a reactive maneuver to counter laser weapons. Spinning the munition is a proposed active countermeasure;[190] this approach would add minimal complexity to most weapons’ designs but might decrease the laser’s lethality. Or a deliberate reactive maneuver might allow the target to rotate to expose a shielded surface to the laser or deny the laser dwell time on sensitive components. The most important thing to recognize with these “maneuver” countermeasures is that the laser is still providing utility. A reacting target is focused on survival. The target is no longer pursuing its primary purpose, or at a minimum, it is less effective at its primary purpose while executing laser countermeasures.

Reactions that directly counter the laser system are also possible. If the laser system relies on radar or EO/IR sensor technology, standard countermeasures apply (e.g. chaff, jamming, flares, LAIRCM, tactics). Again, the laser system still provides utility because the target is less effective at its primary mission while executing countermeasures. Further, countermeasures such as jamming may create new vulnerabilities in the future (e.g. vulnerability to anti-radiation

missiles). Over time, it is more likely that laser-based sensors or advanced passive sensors will inform the laser kill chain.

The most promising future countermeasures are in counter-sensor and counter-directed energy (DE) roles. Laser weapons add a new countermeasure against conventional weapons. An aircraft with a self-defense laser (a defense against air-to-air missiles) could wait until the adversary's air-to-air missile was within close range to obtain a hard-kill against the incoming missile. Or, as a counter-sensor example, the self-defense laser could attempt a soft-kill at longer range (a countermeasure) either against the threat missile's sensors to prevent guidance or against the aircraft itself to prevent (or degrade) launch.

If a self-defense laser can be used as a countermeasure in this manner, a laser can also be employed as a counter-countermeasure against these possibilities. In this context, the benefits of a laser weapon are thwarted by another laser weapon. In a counter-DE example, a laser weapon system (a counter-countermeasure against the self-defense laser) could respond in a fast-reacting counter-DE role to destroy or degrade the performance of the self-defense laser by targeting the sensing components in the kill chain or damaging the optics that are already stressed from self-defense use.

As the innovation cycle continues, even more futuristic countermeasures will be created. For example, the military continues to invest in research that could one day create a "plasma shield" to protect from directed energy weapons.[191] The Joint Nonlethal Weapons Directorate developed the Plasma Acoustic Shield System with the company, Stellar Photonics; currently, the system uses laser bursts to create a plasma in the air as a distraction and warning device.[192] As new technology becomes available, this technology may offer a method to absorb or deflect

directed energy weapons.[193] However, there are too many research challenges and design constraints to consider this a serious detractor for laser weapon performance in 2045.

Aside from countermeasures, one of the most commonly cited arguments against laser weapons is the lack of an all-weather capability. Artificial obscurants or smoke screens could even be used as part of a ground defense countermeasure. But weather has always constrained warfare, contributing the "fog of war" and tactical constraints. Despite much anecdotal concern over the lack of an all-weather capability, there is evidence that suggests these hurdles are not black and white. Global weather patterns, seasonal weather patterns, and the theater of operations will all influence laser performance.[194] Weather certainly degrades performance, but a laser can still provide utility. Technology is also improving laser performance in weather through higher power, longer dwell times, and active beam control. In 1999, Boeing's Tactical High Energy Laser Fighter Study recognized that weather degraded laser propagation, but also states that, "Results show that the presence of clouds and operation of a HEL fighter need not be mutually exclusive events."[195] Studies for the Airborne Tactical Laser (ATL) considered varied climates from Korea to the Arabian Gulf, from hot and humid to cold and clear. The analysis showed effective laser ranges for 80% of the time in both regions; the Arabian Gulf ranged from 16 to 24 km and Korea ranged from 8 to 30 km.[196] Certainly, weather affects performance, but tactical utility remains. The United States Army's HEL MD completed tests at Eglin Air Force Base in 2014 that demonstrated capability against mortars and UAVs with a 10kW system in "very laser-unfriendly foggy, rainy, and windy maritime conditions."[197] However, in a recent analysis of alternatives for a ground-based defensive system, laser weapons were considered "unsuccessful in fog, rain, and sandstorms."[198] The lack of a true all-weather capability for laser weapons continues to detract from their perceived utility compared to kinetic systems, and the

United States needs to better understand the laser's performance degradation in weather to alleviate these concerns.

Employment tactics may also provide countermeasures to reduce the effective range or decrease the effects of laser weapons. Laser weapon employment is most effective at high altitude due to the effects of the atmosphere, and airborne platforms might maximize their laser performance for air-to-air and defensive requirements at high altitude. However, if the aircraft needs to penetrate a directed energy IADS, tactics might require lower altitude flight where higher atmospheric absorption, line of sight, and speed reduce effective laser power and dwell time.[199] Aerial relays are already proposed to allow ground-based lasers to overcome these limitations against low-altitude targets.[200] An aerial relay is essentially a flying "mirror" or relay optic that can redirect laser energy from a ground-based laser to a target.

Avoiding, or remaining outside of, defensive weapon range-rings has always been an effective tactical countermeasure. However, ground-based lasers hold an inherent power advantage, which tilts the advantage to the defensive. This scenario was described during an NRC workshop on directed energy in 2013:

> With respect to Red Force use of DEW systems…an adversary would likely have an asymmetric advantage in that large, heavy DEW systems can protect fixed bases, whereas the U.S. Air Force has to address difficult SWaP [size, weight, and power] issues to have DEW systems that are practical for use on aircraft.[201]

Gies calls this the "primacy of defense" due to the fact that "fixed sites can be constructed to make maximum use of large power sources and the range of a directed energy weapon is directly related to the power available."[202] Line-of-sight offers a potential limitation for high-power ground systems, but aerial relays provide a solution to this tactical countermeasure. Aerial relays both extend the range of ground based laser weapons and also overcome line-of-sight challenges. But does this give the ultimate advantage to defensive systems? The answer is most likely no.

The different pace of laser weapon advancement, different operational tactics, and other complimentary capabilities will likely lead to vulnerabilities in a directed energy IADS. At a minimum, aerial relays add another set of vulnerabilities to the kill chain; disrupting any of the ground or airborne links could disrupt the kill chain.

For every weapon, there will be constraints, counter-tactics, and countermeasure. For every countermeasure, there will be consequences, more counter-tactics, and counter-countermeasures. The tactics and technologies for offensive and defensive lasers systems will not alter this truth. However, these countermeasures will have significant influence on the direction of research and future capabilities. Further, these countermeasures will drive tactical and operational decisions on how to generate the most utility from laser weapons in the future.

The Future of Laser Weapon Technology

Making predictions about future technology is fraught with danger particularly when projecting thirty years into the future. A multitude of assumptions underlie the predictions for supporting technology and even the world environment. Many of today's programs are likely to reach the warfighter by 2030 while today's basic science and research may not see application until 2045. In the case of laser weapons, the predictions must consider current technology, promising new research, and the constraints of physics. These predictions make defensible assessments of future technology that will frame the discussion on the strategic and operational implications of laser weapons.

The following discussion will review general studies on the future of laser weapons, make interim estimates on the capabilities and limitation of lasers in 2030, and finally estimate the advancements and capability expected by 2045. Remember, the 100 kW laser has often been touted as the threshold for laser utility in tactical applications, and the current research certainly

indicates that mark can be achieved within a decade. As these predictions will begin to illustrate, the laser will be poised to revolutionize the battlefield in 2030, but will become the "price of admission" by 2045.

Laser advances will also continue to be spurred by government research and the broader laser market. Jane's projects the high-energy laser market in the United States to grow from roughly $80 million in 2014 to over $350 million in 2022.[203] As interest in laser weapons has grown, the government and industry have conducted multiples studies over the past two decades to evaluate the utility and future requirements for laser weapons. Some of the key elements of these reports are reviewed below and help bound the research and predictions.

The Air Force has almost continuously investigated potential airborne applications for laser weapons. This review will bypass early analysis in favor of studies considering more current technological advances. For instance, an AFRL study concluded in 1999 "that a tactical high-energy laser fighter aircraft was feasible and possible […] with adequate funding."[204] In 2003, Lockheed Martin conducted a separate Directed Energy Worth Analysis and Vehicle Evaluations (DE WAVE) study for AFRL on the military utility of a notional Laser Strike Fighter (LSF) variant of the Joint Strike Fighter. The results clearly favored future laser weapon applications and noted benefits of increased lethality, enhanced survivability, and reduced missile usage.[205] In 2007, the Defense Science Board Task Force observed that future airborne lasers could "provide manned and unmanned aircraft applications at power levels of tens to hundreds of kilowatts for self-defense and, eventually, precision ground attack."[206]

In 2010, the Air Force Chief Scientist completed a study with a twenty-year horizon to refocus efforts on technologies with the highest potential return on investment. The report evaluated solid-state lasers, fiber lasers, and HELLADS-derived technologies for "active airbase

defense, air vehicle defense, and tactical strike applications."[207] As a result of the study, the Air Force Chief Scientist advocated for investment in twenty-eight areas (from power generation to beam propagation to target effects) in order to bring lasers to the battlefield in the 2030 timeframe.[208]

Clearly, the Air Force is looking to integrate laser weapons on the next generation of fighter aircraft. In 2014, AFRL released a Request for Information to industry to "identify potential laser systems that could be integrated into a platform that will provide air dominance in the 2030+ highly contested Anti-Access/Area Denial (A2/AD) environment."[209] For this future air dominance platform, the Air Force is investigating an operational range from sea level to 65,000 feet and speeds from Mach 0.6 to 2.5. The overall effort seeks to manage risk, understand key drivers of cost, and bound the capability, size, weight, power and beam quality that can be expected.[210] The ongoing research across the industry, AFRL, and DARPA suggests that laser weapon systems will be available for consideration on this future platform. For example, Lockheed Martin's Chief Technology Officer Ray Johnson touted the importance of the fiber laser technology as "game-changing" in future military applications and stated that there are "no physical challenges to achieve 100kW and … 300kW looks quite feasible [for airborne tactical applications]."[211] Lockheed Martin foresees initial applications on larger bomber-sized aircraft then reduced in size to fit on a fighter-sized platform. Lockheed already advertises plans for the LSF, which replaces the STOVL (short take-off and vertical landing) lift fan and drive shaft with the laser system. By 2045, these fighter-sized laser systems in the low hundreds of kilowatts are likely to have air-to-air ranges in excess of 50 km and air-to-ground ranges over 15 km.[212]

There have been similar studies conducted on laser weapons for ground-based and naval applications. The Army recently conducted an analysis of alternatives for the Indirect Fire

Protection Capability Increment 2 (IFPC II). A 100-kW HEL system had the highest score on the "ratio of threat kills" compared to the other conventional alternatives. Further, the HEL system did well on life-cycle cost comparisons because there were no missile or bullet consumables. However, the HEL system fell short due to the moderate technical risk, the lack of an all-weather capability, and the Army leaderships' resistance to HEL for base defense.[213] The Congressional Research Service analysis on Navy shipboard lasers advises that in the next decade (mid 2020s), higher power laser systems could provide the "ability to counter a wider range of surface and air targets at ranges of up to about 10 miles [16 km]."[214] At a 2013 workshop for the NRC, participants indicated that "the existing and emerging Army and Navy programs for DEW applications will progress more quickly with high power DEW systems suitable for Air Force missions becoming feasible on a longer time frame."[215]

All of these studies and ongoing research contribute to predictions for the 2030 timeframe. By 2030, fiber lasers are expected to achieve a "multi-hundred kilowatt laser with near-diffraction-limited beam quality."[216] DARPA's Endurance and Flash programs support these conclusions. Other solid-state laser technology is predicted to meet similar power levels and efficiency. In 2030, free electron lasers will likely demonstrate power in the low hundreds of kilowatts with research ongoing to extend to the megawatt class.[217] Pulsed and continuous power operating modes will allow some tailoring of weapon effects. The current development vectors also suggest that by 2030, laser weapons will already enjoy a limited role on the battlefield. Around the world, ground-based defensive laser weapons will be common with powers from 10 to 100 kW and effective ranges for hard kills up to 10 km. The United States will maintain a technological advantage and these ground-based lasers will achieve higher power (likely 200-300 kW). The United States will also introduce airborne laser weapons as podded

(50-100 kW) and internal systems (150-250 kW) for tactical aircraft and UAVs. For high value airborne assets (e.g. AWACS, tankers) the podded system value represents a likely weapon class for self-defense roles. As a reference from 2007, the Defense Science Board Task Force predicted "robust aircraft self-protection" from 5 to 20 km with laser power between 50 to 100 kW.[218] Strategic laser research will continue, but is beyond the scope of this analysis. Overwhelmingly, the indications suggest that these power levels, size, and other requirements are reasonable for 2030.

Despite the impressive progress made on laser weapons, technical limitations will constrain this early generation of laser weapons. Duty cycle, altitude effects, and weather are always considerations, but early generations of laser weapons will be particularly affected. For example, early laser weapons may have limited duty cycles to overcome input power constraints or high temperatures in the lasing medium. Lockheed Martin engineers anticipated a 33% duty cycle for the LSF concept (with 10% laser efficiency) in 2006 (although higher laser efficiencies are now achievable).[219] "Deep magazines" may only be relative for the first generation laser weapons. A potential laser design for the Avenger RPA internal weapons bay might require a recharge time of 2 to 4 minutes between shots.[220] Similarly, DARPA's Flash program is reported to have a 30-shot magazine.[221] Air-to-air and self-defense laser weapons will show markedly better performance at higher altitude (over 30,000 feet) where the atmospheric effects are lower. Similarly, weather, cloud cover, and atmospheric effects will also have greater negative effects on early laser weapons. But ultimately, it will be the tactical considerations of how the laser is applied to combat that define its revolutionary potential in 2030. Although the laser weapons in 2030 will still be relatively primitive, tactical experimentation will uncover the full utility of early laser systems.

Ongoing scientific research and new innovations will help exceed these specifications by 2045. New material types and configurations are still being examined for solid-state lasers, fiber lasers, and free electron lasers that will create steady improvements in power, beam quality, and efficiency. Technology for a second generation of laser weapons might include: tunable wavelengths, improved adaptive optics and flow control, femtosecond pulses, optical arrays with steerable beams and conformal lasers, high power beam splitting, advanced beam control techniques, and low-cost aerial relays. For example, advanced optical arrays may allow the laser to form multiple beams simultaneously for attack, defense, communications, and sensing using a single laser array (similar to how active electronically scanned array, AESA, technology improved radar capabilities). As another example, the Air Force, DTRA, and National Science Foundation funded research to demonstrate an air waveguide.[222] Essentially, they created a laser "pipe" using femtosecond pulses.[223] Future research may provide methods to exploit this channel like an "optical fiber" through the air to place higher power on targets at longer ranges. These examples only illustrate a tiny slice of ongoing scientific research that may provide breakthroughs for the future battlefield.

By 2045, laser weapons will be more ubiquitous for high-end combat as concepts of operations (CONOPS) are better understood and a second generation of laser technology emerges. The cost of laser weapons will fall while the costs of not having laser weapons skyrockets. Mobile ground-based air defense lasers of practical size will achieve up to ~500 kW power and long range when paired with airborne relays. Larger fixed "strategic" systems will achieve multi-megawatt power and even longer range enabled by airborne relays. Airborne tactical applications will achieve up to ~400 kW power and long-range at altitude. "Strategic" airborne applications will be possible up to ~10 MW and may benefit from advances in free

electron lasers. Degradation from weather, altitude, aspect, and other constraints will be significantly reduced compared to first generation systems. Laser countermeasures will be more common and reduce susceptibility. Lasers will have become the "price of admission" for combat in a contested environment by 2045.

To summarize, Table 1 below provides an overview of current laser capabilities and future predictions. The predicted performance is broken down into six main categories for convenience as follows: United States and foreign systems, strategic or tactical applications, airborne or ground-based systems. The table also highlights significant research and development where it adds value. These predictions are assimilated from the body of research reviewed for this project and include the author's assessment on future capabilities. The laser power levels provide the best indication of performance for the future systems. The ranges attempt to add context to the power estimates; however, as already established, the effective range of a laser system relies on a huge number of variables and does not lend to a neat prediction. Ultimately, these capabilities will define the strategic and operational implications for combat in 2045.

		Present (2015)	~ 2030	~ 2045
Ground	Tactical	**U.S. Ops: 30 kW (~2 km)** U.S. Demo: 10-100 kW (2-10 km) **Foreign Ops: Unknown** Foreign Demo: 50 kW (< 2 km)	**Worldwide Ops: 10-100 kW (2-10 km)** **U.S. Ops: 200-300 kW (~10-25 km)** U.S. Demo: Aerial relays Foreign Demo: 150-250 kW (~**5-15** km)	**Worldwide Ops: 10-500 kW** • **Direct fire (~2 km - LOS)** • **Aerial relays (LOS - 150 km)**
Ground	Strategic	U.S. Demo: >2 MW (Unknown) • Analyzed air & space relays Foreign Demo: ~MW (Unknown)	U.S.: Not Considered **Foreign Ops: ~1-5 MW (~450 km)** Foreign Demo: Aerial relays	U.S.: Not Considered Foreign Ops: **<10 MW (~600 km)** • **Aerial relays operational**
Airborne	Tactical	U.S. Demo approaching: • Internal: 150 kW (~10-30 km) • Podded: 30-50 kW (~5-10 km) Foreign: Unknown	**U.S. Operations:** • **Internal: 150-250 kW (~20-50 km)** • **Podded: 50-100 kW (~5-20 km)** • **Air-to-Ground: 5-20 km** Foreign Demo: 30-100 kW (~2-20 km)	**U.S. Operations:** • **Internal: 300-400 kW (~50+ km)** • **Podded: 50-150 kW (~10-30 km)** • **Air-to-Ground: 10-30 km** **Foreign Ops: 50-150 kW (~10-30 km)** • **Air-to-Ground: 5-15 km**
Airborne	Strategic	U.S. Demo: • ABL (COIL): 1-2 MW (~300 km) • HALE Research: 200-300 kW Foreign Demo: • Russia A-60: ~1 MW (Unknown)	**U.S. Ops: 1-5 MW (~450 km)** U.S. Demo: Airborne FEL Research Foreign Demos: ~1-2 MW (~300 km)	**U.S. Ops: 1-10 MW (~600 km)** • **Air-to-Aerial relays operational** **Foreign Ops: ~1-5 MW (~450 km)**

Table 1: Author's Assessment of Future Laser Weapons

Laser Weapons: Implications and Obstacles

The future operational and strategic implications of laser weapons are enormous. All sides will employ laser weapons, but lasers will not completely replace other weapon systems in future combat. Laser weapons will complement conventional weapons while at the same time providing a potentially decisive advantage to the nation with the best technology and strategy. Beason describes this future:

> Advances in science and technology will make their way to the battlefield and will change the nature of warfare. When lasers…are introduced on the battlefield, they will be supplementing the weapons of the past—bullets, bombs, and missiles.[224]

The laser will revolutionize combat tactics. At the tactical and operational level, lasers operate at the speed of light with deep magazines, address force protection challenges, and provide flexible high-precision effects. Strategically, lasers alter the cost exchange, adjust the offensive-

defensive force balance, and enhance the military's existing capabilities. Over the long term, these same potential benefits will also be available to the adversary. The United States will cede the advantage to the adversary if it does not incorporate laser weapons first. In order to compete on this future battlefield, each nation must employ laser weapons—the price of admission.

The laser's operational and strategic implications must be derived from the laser's advantages and disadvantages to predict their most likely future role in conflict. The following broad implications will be expanded throughout the remainder of this discourse:

- Laser weapons offer solutions for current and future challenges—both strategic and operational
- Laser weapons will revolutionize airpower projection but will quickly become the "price of admission" for future combat
- The side with the most advanced laser weapons and the best tactics will have a distinct advantage in future combat
- Future mission priority for laser weapons will be: Counter-Directed Energy, Counter-Sensor, Area/Self-Defense, Offensive Fires
- Failure to incorporate defensive laser weapons or failure to defend against laser weapons will increase vulnerability to attack
- Failure to incorporate laser weapons into offensive operations will limit combat effectiveness
- Despite the progress in laser weapon research, there are still significant obstacles to implementation

Innovation, Counter-Innovation and the "Price of Admission"

The trend of innovation and counter-innovation in warfare is well established. The current and future prospects for laser weapons and countermeasures are reasonably understood. From this knowledge, one can make predictions about 2045. Laser weapons reset the tactical dynamic and redefine the utility of legacy weapons, "especially in the competition between

offensive and defensive capabilities."[225] New concepts of operations (CONOPS) must be developed to integrate the current and future offensive and defensive relationships. But how will laser weapons influence future combat?

The full utility and range of implementations for laser weapons still cannot be known. DTRA and SAIC foresee novel applications for lasers from state and individual adversaries.[226] Innovation cycles almost always generate surprise. This discussion will look at the broad laser and countermeasure trends, offensive and defensive relationships, and ground and air-based platforms likely to occur by 2045.

There are four broad categories for laser weapon distribution in the future: 1) red and blue conventional, 2) red conventional and blue with lasers, 3) red with lasers and blue conventional, and 4) red and blue with lasers. Current research by all parties shows that the "conventional only" scenario can be dismissed as unlikely due the research momentum in the United States and around the world.

The next two scenarios provide a lopsided balance of power and are equally unlikely to materialize. But these scenarios both deserve discussion before they are removed. The future in which the United States develops laser weapons and the adversary does not provides another "throw-away" future scenario for the purpose of this discussion. First, the trends in foreign laser research suggest future roles for laser weapons across many foreign militaries. Second, detailed analysis of this scenario does not add value to the discussion. In this lopsided power scenario, the United States' laser weapon advantage merely extends the historical technological asymmetry. Finally, the same laser weapon applications that extend the United States' advantage in this scenario also exist in the final scenario that will be addressed. While this

scenario will likely play out against some non-peer adversaries, it will not drive innovation for combat in a highly contested environment.

In the third scenario, the United States cedes advantage to the adversary if it does not operationalize laser weapons. In this hypothetical scenario, the adversary develops and employs laser weapons and layers them into an already challenging A2/AD strategy. The lasers' advantages in speed and magazine depth allow more robust defense against even the newest offensive technologies in 2045. The adversary's laser-equipped IADS is capable of targeting the United States' offensive aircraft and incoming precision weapons. Eventually, a large enough swarm could overwhelm these laser defenses; however, the cost and delivery requirements for this swarm will be inefficient and may prove untenable. For a large swarm, the individual weapon cost must be low, which will require design compromises in speed, stealth, and survivability and leave the low-cost munitions more vulnerable to laser defenses. In contrast, more advanced swarms with laser countermeasures, which would increase the swarm's survivability against laser defenses, may prove too expensive to implement as a campaign-wide tactic. For example, the price goal for a Navy countermeasure to protect sensors against directed energy weapons was $10,000 per unit.[227] Expensive high-speed systems may provide some capability to strike against the laser IADS, but the cost exchange is unfavorable, and the requirements for a large stockpile of expensive weapons may be prohibitive, particularly if the technology turnover rate is high in order to maintain an advantage. Laser employment against the United States' ISR network could further complicate operational effectiveness. Even against an adversary without an airborne laser capability, the increased challenge is evident. The lopsided power balance that exists when only one side employs lasers is precisely the condition that makes an "arms race" between laser innovation and counter-innovation likely.

The final scenario is the most likely based on current trends in laser research and the pattern of strategic competition over technology; both sides will develop and employ laser weapons. It is this scenario that shows how significantly the tactics and strategy of air superiority and airpower projection will change in the future. The real questions for the future are: What are the CONOPS for implementation? At what rate do enabling technologies proliferate? And, what are the implications for strategy? Certainly in this scenario, the side with the most advanced laser weapons and the best tactics will have a distinct advantage in future combat.

Operational Implications for 2045

The operational implications for laser weapons in 2045 will be driven by a cycle of innovation and counter-innovation in an effort to solve operational and strategic challenges. This section explores the cycle of innovation and allows the operational implications to unfold through the course of analysis. Ground-based lasers will be implemented—and discussed—first. Analysis follows on the future of airborne laser weapons and potential operating concepts. And finally, air-to-ground offensive laser capabilities are discussed.

The first operational application of laser weapons is likely to be for short-range point defense (~10-100 kW) with systems such as the LaWS, HEL MD, IRON BEAM in Israel, Rheinmetall's system in Germany, or China's indigenous system. One of the driving factors behind laser weapon development is the "proliferation of precision" including guided rockets, artillery, mortars, and missiles.[228] These point-defense systems are the closest to being operationalized and have direct payoff against these precision systems and UAVs. Defensive laser systems serve an immediate operational need, and future systems with higher power levels and longer range meet a challenging anti-cruise missile gap in cost-effective defensive systems. The CSBA supports the laser's role against future precision guided weapons (rockets, artillery,

mortars, and missiles), but they raise operational concerns that nearby land forces could still conduct saturation attacks or use "hardened" rounds that would pose a challenge for laser systems in a base defense role.[229] Large missile swarms could also overwhelm laser defenses, but a significant cost and delivery burden is imposed on the attacker. The potential to overwhelm laser defenses is unlikely to deter investment because alternative kinetic concepts are also vulnerable to saturation and swarm tactics. Further, the fiscal and operational costs of alternatives to implementing laser defenses remain high. Defensively, the United States needs a laser weapon layer to protect our bases for power projection in an A2/AD environment, and failure to incorporate laser weapons into defensive operations will leave forces more vulnerable to attack.

This analysis suggests that for ground-based defenses, all advanced IADS will have a laser (or directed energy) element by 2045. Worldwide ground-based defensive systems (~150-250 kW) will emerge through 2030, and by 2045, ground-based laser defensive system will be nearly ubiquitous with numerous mobile and stationary systems providing a variety of roles (~10-500 kW). More lasers systems will operate in mutually supporting area-defense roles and integrated fully as laser IADS (opposed to earlier point-defense roles). The CSBA agrees and envisions laser weapons providing an advantage for base defense in a future A2/AD environment.[230] Similarly, the Defense Science Board Task Force argued that ground-based defensive laser systems are an attractive option for countries with A2/AD strategies.[231] The inherent technology and design considerations for laser weapons may even favor these defensive strategies. Countries pursuing area denial strategies are likely to adopt the laser in defensive roles, thus increasing the defensive advantage.

Airborne self-defense lasers are another early application for lasers that is likely to be operationalized in the United States by 2030. Airborne self-defense lasers increase survivability against a conventional technologically advanced IADS and air-to-air missiles. By 2030, internal airborne self-defense lasers (~150-250 kW) and podded systems (~50-100 kW) will begin to emerge on the battlefield. Refueling tankers and HVAA will likely employ self-defense systems equivalent to these podded designs. Early laser systems will likely focus primarily on defenses—targeting the threat missile or threat missile's sensors only. Northrop Grumman suggests, "because aircraft defensive lasers can shoot down SAMs or AAMs as they are fired at the defended aircraft, commanders could have the option to begin strike operations before either a SEAD [suppression of enemy air defenses] or air supremacy campaign is complete."[232] Tankers and HVAA assets may be able to operate in what is now considered a non-permissive environment.[233] The incorporation of airborne self-defense lasers into offensive air operations will significantly increase survivability and the chances for success.

Since it is likely that threat countries will employ laser IADS, the evaluation must also consider the implications for the United States' offensive strike missions. It has been established that ground-based laser weapons are likely to include both point and area defense systems in 2045 (~10-500 kW). Once adversaries possess laser IADS, air-to-ground weapons and cruise missiles are likely to be vulnerable to the laser IADS and potentially impotent. The laser defenses must be considered. A 2005 report by Northrop Grumman on operational implications of laser weapons warns strongly on the need to "… avoid implementing weapons that can easily be countered."[234] The United States will face two familiar choices for attack: either overwhelm the laser IADS with swarms or counter the laser IADS directly. Countering the laser IADs offers the greatest long term potential. In the short term, passive and active countermeasures against

laser weapons must be balanced against other variables for swarm weapons, such as cost and survivability. The CSBA makes a similar case for a point-defense scenario against guided rockets, artillery, mortars, and missiles.[235] In 2030, early generations of laser-IADS threats are likely to be overcome by swarm or countering traditional elements of their laser kill chain. For instance, some early systems are likely to have limited numbers and poor coverage while still requiring radar-tracking elements. Jamming the radar might be effective, but SEAD weapons (e.g. HARMs) are likely to be shot-down and ineffective at destroying a laser IADS (as long as the quantity of weapons is below the saturation point for a swarm attack).

By 2045, these laser IADS will likely be much more robust against swarms and incorporate less vulnerable kill chains. These higher power systems will also benefit from aerial relays that extend the laser's engagement range, provide a look-down aspect against low altitude targets, and offer multiple aspect shots against each target. Against this more robust laser IADS, a counter-sensor or counter-DE laser weapon will likely be required and more efficient. Experts briefly discussed the concern over "Red Force DEW systems" at a 2013 NRC workshop on DEW, but little consensus emerged beyond the need for a capabilities-based assessment to further explore the concept.[236] The Air Force's Center for Strategy and Technology also highlights the counter-sensor battle[237] and the importance of weapon survivability and capability.[238] Countering the sensors or the laser weapon itself will be essential even if the laser does not provide the final damage mechanism. The laser weapon might merely suppress, jam, or degrade the laser defenses to allow conventional munitions to engage the target. An analysis of alternatives between laser weapons and swarms versus the laser IADS depends on the rate of progress across many fields of research. A new CONOPS may evolve for the suppression of enemy laser weapons (SELW) using counter-sensor and counter-DE. In order to maintain

effectiveness, the United States will be required to suppress enemy laser defenses as a precursor to offensive operations. Laser weapons in a counter-sensor or counter-DE role provide an effective and efficient method to suppress defenses and therefore enable conventional munitions. Comments from experts support this argument, "Countering Red Force defensive DEW might be best done by CONOPS that combined DEW and kinetic weapon capabilities."[239] Through the counter-directed energy and counter-sensor roles, laser weapons will be essential enablers that "escort" more conventional offensive kinetic air-to-ground weapons.

If the adversary's IADS includes higher power "strategic" laser defenses (~1-5 MW), the offensive problem is more challenging. Swarm and counter-sensor/counter-DE solutions are much less effective. Swarms face increased vulnerability due to the longer exposure: both longer range and longer time-of-flight. Eventually, even low altitude swarms are unlikely to succeed due to aerial relays. The United States would also be less effective using laser suppression against high power systems since ground based systems have an inherent advantage in size, weight and power. The availability of high power provides longer range and the first shot. The greatest potential might be to use offensive lasers in a counter-sensor/counter-DE role to again suppress these large defensive laser IADS from operating. However, these ground-based systems can also conduct counter-sensor/counter-DE functions, again at much longer range, and are likely to defeat any offensive forces before they can threaten the system from the air. Experts suggest, "An open question is whether airborne DEW weapons would be successful in 'jousting' with the larger, more powerful Red Force [ground] systems."[240] Fortunately, these laser defenses would be much larger and in fixed positions so asymmetric means could hold these systems vulnerable. For example, special operations forces could use directed energy or conventional methods to suppress or destroy these high power laser defenses prior to offensive

air operations. Further, if these systems relied on airborne relays to increase coverage, the relay systems themselves could be targeted with similar effect. Once these high-power laser systems are defeated or degraded to direct line of sight (no relays), then low-altitude swarm or airborne suppression techniques are more plausible. Ultimately, the suppression of these long-range laser IADS is essential to enable future conventional operations.

Now that the innovation, counter-innovation cycle is established for laser IADS, it is easier to envision the future of air-to-air combat. Although the United States may possess airborne laser weapons (~50-250 kW) by 2030, potential adversaries are likely to be slightly behind—both with respect to timing (~2045) and power level (~50-150 kW). In 2030, airborne lasers will perform limited missions and are unlikely to saturate the airspace. The self-defense benefits of achieving a hard kill against oncoming air-to-air missiles have already been established. But the more effective goal is to destroy the adversary's aircraft or prevent the launch. Unfortunately, the next-generation air-to-air missiles are likely to have longer ranges than laser weapons (for hard kills) for both the United States and adversaries. The first shot will belong to these conventional weapons. But, will an adversary even take a long-range conventional shot if airborne self-defense lasers give a low probability of success? As discussed earlier, the United States and later the adversary will be able counter these air-to-air missiles with the airborne self-defense laser. In a concept study, the Laser Strike Fighter (with a 150 kW laser) "showed an increase in Blue Force survivability and an increase in Red Force attrition relative to the same counter-air scenario run…without the HEL weapon system."[241]

Long-range laser shots will be available for the counter-sensor mission in order to defeat the threat missile sensor or even prevent launch. Similarly, counter-DE roles deny or destroy the adversary's offensive or defense use of lasers (or directed energy more broadly). Like the

CONOPS against ground-based laser IADS, the suppression and destruction of enemy laser defenses is essential to air-to-air combat as well. The airborne laser may achieve hard kills against targets at close range, but more likely the laser weapon will be used at longer range to suppress the laser system sensors or optics, or even against traditional sensors on enemy fighter aircraft and missiles. The key will be blinding or damaging the sensors at the longest range possible. For example, destroying the infrared sensors of an air-to-air missile while still loaded on the aircraft might prevent missile launch. Or, destroying an infrared search and track (IRST) system[242] might degrade targeting, reduce situational awareness, or force tracking to a different system that is easier to detect and counter (e.g. radar). Further, damaging the optics on the enemy's self-defense laser would suppress the defensive system—an effective mission kill. Going further, the suppression could also allow conventional air-to-air missiles to follow-up for a kinetic kill. At closer range, the laser will even be able to achieve a direct hard kill against the aircraft. While laser weapons may first be introduced as defensive systems, they will quickly gain offensive roles.

More parity in airborne laser weapons is likely by 2045. For the United States, airborne laser systems (up to 400 kW) will be ubiquitous for all modern aircraft and podded systems will provide an alternative (~50-150 kW). Laser systems will also be common on adversary aircraft at tactically significant power levels (~50-150 kW). An analysis of alternatives will be required to compare external podded additions against internal modifications for both large heavy aircraft and fighters. In this environment, it will be essential to conduct this counter-sensor and counter-DE battle at range before employing traditional weapons. Further, the United States must employ countermeasures and tactics to preserve sensors and lasers against adversary lasers. In 2045, laser counter-countermeasures become essential. Offensively, the United States will need

lasers to survive against adversary threats. Adversaries will aim to counter the United States' sensors and directed energy systems with soft kills in order to enable hard kills with either lasers or conventional missiles. Because of the speed and range requirements, the laser will provide the ultimate system to counter these adversary lasers by targeting the tracking sensors or laser optics themselves. Any offensive strike package will require laser weapon support to be effective. Laser weapons will be the essential enablers that degrade defensive systems and even "escort" kinetic air-to-air weapons. As a result, incorporating laser protection, laser counter-measures, and laser counter-tactics into offensive operations will significantly increase the chances for success.

To project power in this environment, the Air Force will gain and exploit air superiority by prioritizing laser weapons for counter-directed energy, counter-sensor, area/self-protection, and offensive fires. The arguments for prioritizing counter-DE and counter-sensor missions are now well established. In addition to both of these applications, the area/self-protection role for lasers will be essential to the air superiority mission. History has established that air superiority is a necessary precursor for airpower projection. In many respects, the preceding arguments suggest that "laser superiority" may even be a precursor to air superiority.

There are other concepts that could help attain air superiority and demonstrate the priority for area and self-defense roles for laser weapons. Both buddy and self-defense lasers will be important. Buddy defense concepts increase the overlapping field of fire against threat missiles, and tactics can ensure a different aspect laser shot is available against the threat aircraft or missile. Counter-tactics that merely mask a sensitive system by maneuver would be less effective against a combined buddy and self-defense approach. Swarms would be easier to

defeat with a buddy laser, and for low-saturation attacks multiple laser shots against a single target might shorten the overall engagement duration.

By 2045, the ability to divide the laser's total power and simultaneously fire against multiple targets will also be desirable and contribute to the air superiority mission. Ongoing research into optical arrays, such as DAPRA's work on Excalibur, may provide technology to support multiple beams from a single laser weapon. However, other questions still remain. How many layers of overlapping field of view are required for effective defense? What rate of fire is needed to provide defense against a salvo or swarm attack? How will laser power be allocated and prioritized against multiple targets?

As a result of these new operational concepts, significant changes may propagate into aircraft design. Maneuverability, stealth, and speed are less valuable and deserve lower priority in aircraft design when laser weapons are fully integrated. Laser systems, advanced sensors, and laser countermeasures take higher priority. Studies from Northrop Grumman compared laser systems (~25-150kW) to "low-observability alternatives" and emphasized "the increase in aircraft 'autonomy' and flexibility provided by a multi-use tactical HEL system."[243] Also, the susceptibility of the aircrew to laser energy will likely combine with trends in remote and autonomous vehicles to hasten the transition to unmanned aircraft in laser combat environments. Will self-defense lasers be employed from onboard high-value assets and offensive strike "battleplanes" only—unescorted and unafraid? Or will defensive lasers fly on escort UAVs that are slaved to protect offensive or defensive assets in a "buddy" or area defense role? For penetrating strike missions, wargaming will be required to compare large expensive self-defending multi-mission aircraft and strike packages with multiple lower-cost mission-specific (or modular) UAVs that include laser buddy defense for the strike package. Similarly,

wargaming can compare laser self-defense for HVAA and refueling tankers versus buddy defense from escort UAVs. Certainly traditional fighter-bomber history suggests that the package supported by multiple laser UAVs might offer more flexibility and survivability. Another potential advantage of the laser UAV performing a “laser escort” role is that strike packages could be tailored against the threat. “Laser escort” UAVs would have more flexibility for mission allocation—providing defensive combat air patrols, HVAA escort, traditional fighter roles, or offensive air-to-ground missions. Fundamentally, the Air Force must develop a long-term concept of operations and an implementation strategy for laser weapons.

Finally, the laser provides offensive fires and will also create direct effects in an air-to-ground role. With relatively minor additions, these aircraft will also be capable of using their laser weapon to strike susceptible targets on the ground, including both soft and hard targets. These tactical airborne lasers will likely have effective ranges from 5 to 20 km by 2030 (50-250kW) and from 10 to 30 km by 2045 (50-400kW). The spectrum of potential targets is extremely broad. Sensor, optics, and critical components could be targeted at lower power levels, and at higher power levels, harder targets can be damaged or destroyed. For example, in 2009, the Airborne Tactical Laser was demonstrated against a truck’s engine block.[244] Inevitably, once aircraft are equipped with lasers, the Air Force will innovate new air-to-ground applications that provide military utility.

So where do theses broad interactions leave laser weapons for the future battlefield? The decisions are being made today that are steering the innovation, counter-innovation cycle and defining concepts of operation for the future of laser warfare. Certainly, new and novel techniques will revolutionize and solidify how the laser is used in combat, and by 2045 laser

weapons will be ubiquitous for high-end combat. Operational requirements will force laser weapons to become the “price of admission” for operations in a highly contested environment.

Strategic Implications for 2045

Laser weapons will also have strategic implications for the United States in 2045. The ultimate value of any weapon system is driven by its ability to create strategic effects, but at the same time, any secondary effects must also be considered. The following discussion analyzes those strategic effects in a future highly contested A2/AD environment. The implications for laser weapons include both operationally derived strategic utility and inherent strategic qualities. The strategic implications of laser weapons in an A2/AD environment include: 1) preserving conventional capability for operational effects, 2) increasing survivability to undermine asymmetric strategies, and 3) creating lethal and non-lethal fires to achieved strategic effects. Further, the inherent strategic qualities for laser weapons include: 4) de-escalating pre-conflict hostility, 5) resetting the cost exchange for the defense, and 6) imposing fiscal and operational costs on the adversary. In total, these strategic implications all support continued efforts to integrate laser weapons into the United States military.

Laser weapons fill a strategic need because they are required to preserve the utility of existing forces. With an appropriate concept of operations, laser weapons assure continued utility of all conventional forces through the suppression of enemy laser weapons. Without laser weapons, the strategic utility for other weapon systems is compromised, and the United States risks a degraded ability to project power in the air, sea, land, and space domains. For the adversary, conventional weapon systems might be rendered obsolete if an effective counter for laser weapons is not implemented. This would transfer huge fiscal and operational costs to the adversary. If the United States implements lasers and prioritizes suppression of enemy laser

weapons ("laser superiority"), then the United States can maintain the strategic utility of its conventional weapons inventory and lessen the cost burden of obsolescence. In contrast, denying an adversary "laser superiority" will impose costs on the adversary by rendering their conventional weapons largely obsolete.

The laser weapons' ability to increase survivability provides a significant strategic advantage in an A2/AD conflict. Four commonly cited challenges for airpower in A2/AD environments are: vulnerability of large air bases, inability to bring HVAA and tanker assets within effective range, vulnerability of strike forces to robust IADS, and inability to carry a sufficient quantity of munitions into conflict.[245] Laser weapons favorably address each of these operational challenges and provide a strategic benefit during A2/AD conflict. Amazingly, as of 2013, "DEW [was] not in the defensive solutions being considered by the Air-Sea Battle Office."[246] Although these applications have been alluded to throughout this analysis, it's worth re-examining the opportunities that a laser provides. Integrating ground-based lasers, aerial relays, and defensive laser UAVs into future air base defense architectures will reduce vulnerability to adversary missile attacks. After the suppression and destruction of the adversary's long-range laser weapons, refueling tankers and HVAA with self-defense lasers or "escort" laser UAVs will be able to enter traditionally "non-permissive" environments, reducing range requirements for strike assets and increasing ISR coverage. The penetrating strike force will be able to suppress laser IADS, provide localized air superiority through laser "buddy" defense, and carry out both conventional and laser strikes against the enemy. Finally, offensive and defensive counter-air and strike platforms will have "deep magazines" allowing more kills per platform and longer "on-station" times.[247] In sum, these survivability benefits at the operational level provide a significant strategic advantage in an A2/AD conflict.

The laser also provides strategic utility by increasing the "precision of effect." The ability to alter the power output and scale the lethality of lasers offers opportunities to create new effects—or "precision of effect." The additional non-lethal mode creates a new ability to tailor strategic effects, and the strategic implications of these non-lethal and ultra-precise effects will be evident on the future battlefield. Militaries will continue to seek low collateral damage and increased targeting efficiency from laser weapons. Depending on the strategic intent, these options provide flexibility and more finely crafted options for creating strategic effect in both high and low intensity conflict. The new strategic implications extend beyond merely the cumulative effects from the tactical or operational level.

In addition to the operationally derived strategic utility, the introduction of laser weapons will also bring specific strategic implications. For instance, the introduction of laser weapons may provide some stabilization and de-escalation for confrontation against A2/AD strategies. Conventional technology seems to favor offensive action for the anti-access role, and the current cost of defensive systems is high. Before forces begin to aggregate in theater ahead of potential combat operations, an adversary following an A2/AD strategy is incentivized to conduct a first strike to deny access to the region and to destroy offensive capabilities before they begin dismantling the A2/AD network. The adversary must use the A2/AD capabilities or risk losing these assets. Against only conventional technology, the adversary's anti-access weapons are likely to be successful; the United States has limited means to counter these attacks. However, robust laser defenses change the risk decision. Since laser weapons provide a more cost-effective defense, it is more likely that the systems can be deployed in sufficient quantity to provide adequate defenses. A first strike against such a well-defended target may not be as attractive an option, thus de-escalating and stabilizing some pre-conflict tension. When equipped

with laser weapons, the United States' power projection forces might provide more of a deterrent rather than being viewed as "vulnerable" at the outset of an A2/AD conflict.

Laser weapons also reset the cost equation for defense against conventional weapons. An electric laser's costs are driven by the price of fuel, and the cost for the threat missile is much higher than the cost of fuel. As previously discussed, laser weapons preformed well against traditional kinetic systems in an analysis of alternatives for short-range ground-based air defense. The CSBA suggests that laser weapons show "potential to reduce DoD's dependence on costly kinetic weapons that require extensive logistics networks to replenish, yielding savings that could be used for other priorities."[248] Additional fidelity can be added to this cost comparison as the life-cycle costs of consumable items are better understood (e.g. optics). Still, these changes reset the cost exchange for defensive actions. "Low cost" defensive systems benefit both the United States and potential adversaries. However, if the United States maintains a power projection strategy and prioritizes suppression of enemy laser weapons, the United States should maintain a laser advantage through 2045 due to the initial technological lead. Whether facing incoming cruise missiles against an air base or surface-to-air missiles against a penetrating bomber, the defensive laser systems will improve the cost exchange for each engagement. Further, lower life-cycle costs for laser defensive systems returns additional resources to offensive operations.

Finally, embracing laser weapons and focusing on suppression of enemy laser weapons imposes costs on the adversary as part of a larger competitive strategy. Ekman defines cost imposition as "a more finely tailored competitive strategy whereby program, posture, and operational concept choices lead an adversary to incur greater hardship – fiscal or otherwise – through disadvantageous competition."[249] Ekman argues, "Prospects for competitive

strategies…depend on …anticipating an adversary's response to a DoD program, posture, or operating concept choice."[250] Adopting new technology such as laser weapons will be no different, and elements of an "arms race" may be likely. The enemy must respond to the addition of laser weapons, and most likely that response will also include lasers. An adversary's failure to develop laser weapons would yield an even greater technological advantage for the United States. The fiscal and operational costs that might be imposed by rendering an adversary's conventional forces largely obsolete have already been covered. Ekman further discusses competitive strategies and how those strategies can drive investments in defense. Power projection strategies impose opportunity costs on potential adversaries because the adversary is driven to a defense response (e.g. A2/AD). The opportunity cost of this defensive posture is a lesser offensive capability. By maintaining a smart offensive focus for laser weapons, the United States can continue to benefit strategically from its power projection posture.

Obstacles to Implementation

Laser weapons have faced many obstacles over the years—both justified and unjustified, technical and non-technical. The obstacles to laser weapon implementation have been under constant scrutiny with opinions from across the field—from the Defense Science Board Task Force to the CRS to think tanks like CSBA and even personal advocates like Doug Beason and Jeff Hecht. Five key trends emerge. In order to successfully field the laser weapon technology and maintain the strategic advantage for 2045, the following obstacles must be overcome: 1) significant technology challenges still exist, 2) an integrated concept of operations is not available, 3) institutional obstacles are delaying transition, 4) lasers suffer from cultural

skepticism, and 5) Air Force and joint doctrine are not ready. Addressing these obstacles will prepare the way to operational capabilities for laser weapons.

Significant technology challenges still exist and have been discussed throughout this analysis. In 2013, a workshop of experts in directed energy suggested that for Air Force applications, "the technology may not be sufficiently mature in aspects that are key to operational capability."[251] The primary technical obstacles appear to be size, weight, and power (SWaP) for more capable airborne systems and lack of a robust all-weather capability. Significant improvements in SWaP have occurred over the past decade and progress is likely to continue. But even at current levels of technology, ground systems will improve ground and air base defenses if properly integrated with conventional systems. Further, lower power airborne applications (at demonstrated SWaP) will also prove useful as an interim capability to develop tactics, gain operational experience, and provide a bridge to future laser weapons. Laser weapons will continue to be limited by weather; however, these weapons will still prove useful when layered to complement conventional weapon systems. Against this obstacle, airborne platforms benefit from the ability to fly above most weather. Airborne and ground-based lasers can still provide useful capability despite the weather restrictions. Certainly, technical challenges remain for laser weapons—the SWaP must be matched to the application for first generation systems and the lack of an all-weather capability should not preclude a laser weapon from operational use.

Another significant obstacle to laser weapon implementation is the lack of a clearly communicated, integrated concept of operation for laser weapons on the future battlefield. In 2007, the Defense Science Board Task Force noted a lack of a clear CONOPS for laser weapons.[252] In 2013, one of the major themes of an Air Force-sponsored NRC workshop asked

whether the Air Force was considering the right applications and CONOPS for directed energy weapons.[253] The following comments from the "warfighter" identify the challenge:

> This is a very complex technology field and the complexity gives a lot of options, which require a lot of resources [to pursue]. A communications plan is needed to explain the options to the operational community and decision makers.[254]

The struggle to identify an appropriate CONOP that garners support from the services and combatant commands remains illusive. In 2009, Krepinevich acknowledged service barriers limited progress toward an operational capability and suggested that the services are more likely to adopt laser weapons if they: "address an important operational problem, sustain a form of warfare with which the Service is familiar, and sustains the dominant sub-groups within the Service."[255] The DoD approach has certainly shifted since that critique was levied and is now more closely aligned to this advice. Recent efforts have focused on lower expectations, earlier implementation, and prototypes for point defense systems. The hope is that as these early systems gain acceptance and combat experience, the warfighter's calls for new laser requirements will accelerate.

Much of the popular discussion for laser CONOPS focuses on the "game-changing" advantage that laser weapons provide for the United States. One of the main arguments of this paper is that a more appropriate question is "how will adversaries use lasers against American interests?" The "game-changing" advantage may still arrive, but history suggests that the answer to this question will have more long-term bearing on the technology, CONOPS, and tactics for future laser weapons. The answer—the United States will face robust laser IADS and counter-sensor/counter-DE tactics. This answer reprioritizes investment and laser weapon employment tactics to focus on the suppression of enemy laser weapons first.

Institutional barriers that plague many technology efforts are also delaying implementation of laser weapons. The classic struggle between "What are the warfighter requirements?" and "What can technology reliably provide?" continues to play out for laser weapons. Beason found that challenges transitioning DEW to the battlefield are significant.[256] Debate continues on whether laser advocates should first emphasize requirements, a demonstrator, or a prototype to create a "win" for directed energy.[257] Lockheed Martin points out that "multiple, compelling applications have emerged [for high energy lasers] as opposed to a single 'killer application.'"[258] Lack of an obvious "killer app" complicates the debate further. In addition to a lack of clear requirements, the business case for laser weapons has not been resolved. Unfortunately, it is difficult to accurately evaluate any game-changing technology due to high uncertainty. In comparison, the cost of conventional alternatives is well understood. Beason agrees that the economics versus conventional weapons provide a challenge to laser weapons.[259] The Defense Science Board Task Force identified competition from proven conventional approaches that achieve similar effects was also delaying implementation of laser weapons.[260] In a similar argument, the CSBA warns of "potentially serious consequences for U.S. national security" if the United States cannot overcome the institutional non-technical barriers that are normally associated with disruptive technology.[261]

Laser weapons also suffer from cultural skepticism earned over decades of overpromising the utility of laser weapons and under-delivering on actual capability and development timelines. The overall lack of credibility for laser weapons has significant consequences and is quite possibly the most significant obstacle to implementation.

Beason found that the early hype of directed energy was an obstacle to implementation.[262] Similarly, the Defense Science Board Task Force cited the history of overly optimistic

expectations as a primary obstacle to implementation.[263] In 2009, the CSBA raised the concern "that this poor past performance could lead decision-makers to downplay or ignore recent advances in laser technologies that, if pursued, could finally yield battlefield applications."[264] In 2012, the CSBA suggested that cultural factors and lack of funding pose a greater barrier to laser weapon development than the state of technological maturity.[265] In 2013, Wong's analysis identified "perceived newness" and skepticism brought on by past failures as leading obstacles to directed energy weapons.[266] Realistically, this should be expected; lasers have been promised for a long time.

Laser weapons require a leap of faith to put trust in a new weapon technology, and the military often drags its feet when adopting disruptive technologies. At a 2013 NRC workshop, a representative of the Directed Energy Senior Advisor Group opined that, "DEW is not currently on the radar screen for senior Air Force leadership."[267] Beason poignantly notes, "For a revolutionary technology such as directed energy, which not only allows a new way of fighting but dictates changes in doctrine, tactics, and strategy, one must be steeled to expect major problems [with acceptance]."[268] Consensus among experts is that laser weapons lack credibility with the warfighter, and the warfighter either does "not understand or accept the opportunities offered by DEW capabilities".[269]

Another significant obstacle to implementation derives from the unfortunate treatment of lasers (and of directed energy more broadly) in Air Force and joint doctrine. The Air Force Doctrine only briefly references directed energy as Electronic Warfare.[270] Contrary to the future direction and uses for lasers, the Air Force Doctrine Annexes for Counterair, Counterland, Targeting, and Strategic Attack do not include references to lasers or directed energy weapons. Joint Publications mirror this treatment of laser weapons; lasers are hidden under the broad

category of Electronic Warfare and further buried under the subcategory of Electronic Attack.[271] Air Force and joint doctrine's implied priority even shakes out to give preference to traditional radar jamming techniques over any directed energy. Even though its future significance is obscured by its place within Electronic Warfare, at least *Joint Publication 3-13.1* makes a concerted effort to outline directed energy technology and acknowledge its "evolving fires applications."[272]

Its true, lasers are hard to categorize. Certain applications like LAIRCM might even belong in the electronic warfare section. However, lasers for direct attack against a target or for intelligence detection and tracking seem out of place and lost under electronic attack. *Air Force Doctrine Annex 3-51 Electronic Warfare* addresses traditional Suppression of Enemy Air Defenses and may offer an approach to integrating the laser concepts:

> In Air Force doctrine, SEAD is not part of EW, but it is a broad term that may include the use of EW. In Air Force doctrine, SEAD is part of the counterair framework and directly contributes to offensive counterair and obtaining air superiority.[273]

A similar treatment of lasers or the SELW concepts discussed in this paper might offer a potential solution. Overall, critical thought is required to more appropriately categorize laser weapons or, at a minimum, break out and distribute the different functions of laser weapons across applicable sections of doctrine. In order to effectively integrate laser weapons into the joint fight, the military will need to move beyond its current doctrinal understanding of laser weapons and directed energy. Directed energy and laser weapons must be disaggregated from "electronic warfare" and treated as a tool—like an aircraft or a gun—with broad application across doctrinal applications. Creating the doctrinal framework for future directed energy warfare will motivate increased awareness and training, gain credibility for directed energy, and stimulate critical thought on the implications for laser weapons. Surprisingly, even as short-

range laser defenses are being deployed, the implications of this new class of weapons are not receiving attention outside of a small community of directed energy experts.

Conclusion

Laser weapons will provide significant tactical utility and new strategic value to warfighting for those that adopt the new technology. The United States faces many challenges preparing to fight and win in the contested operating environments of the future. History shows a continuous cycle of innovation, the introduction and evolution of new technologies, and the integration of new tactical, operational, and strategic concepts.

In 2014 the United States deployed its first defensive laser weapon system on board the *USS Ponce* in the Middle East. Defense contractors are flush with demonstrator systems for ground-based point defense. The AFRL and DARPA continue to make progress toward airborne applications. Foreign countries are aggressively pursuing laser technology. And the maturity, power levels, and lethality of all of these systems continue to grow. With such broad research and operational promise, laser weapons are likely to become ubiquitous on the battlefield for high-end combat by 2045.

Laser weapons will revolutionize tactics and reset strategic calculations for air superiority and power projection in the future. Developing the best laser weapons and tactics and implementing them first is paramount to the United States' interests. While the first generation of laser weapons may unsettle conventional weapons in some scenarios in 2030, the second generation of laser weapons will enter a complex crossfire of innovation and counter-innovation in both conventional and directed energy weapons. By 2045, both airborne and ground-based laser weapons will play a significant role in both air superiority and power projection.

Contested operations will require laser weapons as the “price of admission” for both offensive and defensive systems by 2045, but lasers will not replace conventional weapons. To project airpower in this environment, the Air Force will gain and exploit air superiority by prioritizing laser weapon applications for counter-directed energy, counter-sensor, area/self-defense, and offensive fires against both airborne and ground targets. Most importantly, the pervasiveness of threat laser weapons on this future battlefield means that suppression of enemy laser weapons will become the top priority in future combat. Suppressing the threat from directed energy systems will be the essential enabler for airpower and the use of conventional munitions. In addition, the following truths have been demonstrated for laser weapons during the course of this analysis:

- Strategically and operationally useful—Laser weapons offer solutions for current and future challenges in highly contested environments

- Lasers join the cycle of military innovation—Laser weapons will revolutionize airpower projection but will quickly become the “price of admission” for future combat

- Technology and tactics matter—The side with the most advanced laser weapons and the best tactics will have a distinct advantage in future combat

- Suppression of Enemy Laser Weapons (SELW) first—Future mission priority for laser weapons will be: Counter-Directed Energy, Counter-Sensor, Area/Self-Defense, Offensive Fires

- Defensive necessity—Failure to incorporate defensive laser weapons or failure to defend against laser weapons will increase vulnerability to attack

- Offensive imperative—Failure to incorporate laser weapons into offensive operations will limit combat effectiveness

- Obstacles remain—Despite the progress in laser weapon research, there are still significant obstacles to implementation

The strategic implications of laser weapons also show promise for future conflicts. The laser weapons derive strategic utility from their operational capabilities and inherent strategic

qualities. Operationally, laser weapons create strategic effects by preserving conventional capabilities, directly addressing asymmetric challenges in an A2/AD environment, and creating lethal and non-lethal fires to achieved strategic effects against the adversary.

The inherent strategic qualities of laser weapons include: de-escalating pre-conflict hostility, resetting the cost exchange for the defense, and imposing fiscal and operational costs on the adversary. These strategic implications all support continued efforts to integrate laser weapons into the United States military. The laser's defensive strength may decrease the adversary's incentive for a first strike in an A2/AD environment. Further, laser weapons reset the cost-exchange for defensive engagements and allow a reallocation of resources to offensive operations. Finally, the United States will impose fiscal and operational costs on the adversary by embracing laser weapons and prioritizing the suppression of enemy laser weapons.

Recommendations

The decision to employ lasers is not sufficient to guarantee success in future combat. The successful implementation of lasers onto the future battlefield requires planning and action now to deliver the capabilities needed in 2045. The United States must take deliberate actions to continue the development of enabling technologies, optimize the employment concepts for laser weapons, overcome obstacles to implementation, and integrate these concepts with existing tactics and strategy. Although much of this work must occur in a classified environment, there is significant advocacy and education needed in common discourse. The United States must continue to fund and prioritize the research, development, and procurement of laser weapon systems. For this future vision to unfold, the United States must do the following:

- Continue to invest in directed energy and laser weapon applications—prioritize counter-directed energy, counter-sensor, area/self-defense, and then offensive fires.

- Adjust the focus—the current discussion on laser weapons overemphasizes "what lasers can do for the United States" and underemphasizes "what lasers can do *against* the United States."

- Prepare for future laser threats by developing technology for the Suppression of Enemy Laser Weapons and requiring all new weapon acquisitions to be assessed against future laser threats and evaluated for the inclusion of laser countermeasures.

- Sink the *Ostfriesland*! Prototype laser weapons need to shock the system during conventional force exercises to gain acceptance and demonstrate the absolute necessity for laser weapons in future combat.

- Build an integrated narrative—publish an unclassified broad official concept of operations for laser weapons, similar to this paper. Conduct "road shows" at the classified level for tactics talks, major exercises, and combatant commands to integrate laser requirements with future planning.

- Think critically and educate the force—Do not be afraid to discuss the future! Generate open discussion and intellectual debate on the implications of laser weapons building on the service's integrated narrative (e.g. with Airmen, the military, scholars, the public, the tactical community, and within professional military education)

- Conduct an assessment to determine the most appropriate organization and treatment for directed energy in joint doctrine. Rewrite and reorganize Air Force and Joint Doctrine to prepare for the future role of directed energy.

- Conduct additional research to evaluate swarm tactics against laser defenses. Understand key performance parameters, design characteristics, and the trade space for different operational scenarios.

The continued emphasis on laser weapon technology and the implementation of these recommendations is essential to both air superiority and power projection in the contested environment of 2045. In the cycle of innovation, laser weapons have just fired a warning shot at the speed of light and announced the onset of a new era of directed energy combat.

The United States must be prepared and not lose momentum because laser weapons will become the "price of admission."

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